+1-2918

4042-F m/5

WADC TECHNICAL REPORT 52-59

DO NOT DESTROY
RETURN TO
TECHNICAL DOCUMENT
CONTROL SECTION
WCOSI-3

AD A075870
AS AII NO. 15714

STUDIES ON BURNER FLAMES OF HYDROGEN-OXYGEN MIXTURES AT HIGH PRESSURES

APPROVED FOR PUBLIC RELEASE-
DISTRIBUTION UNLIMITED

Reproduced From
Best Available Copy

WRIGHT AIR DEVELOPMENT CENTER

20011214247

79 10 25 252

NOTICES

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The information furnished herewith is made available for study upon the understanding that the Government's proprietary interests in and relating thereto shall not be impaired. It is desired that the Judge Advocate (WCJ), Wright Air Development Center, Wright-Patterson Air Force Base, Ohio, be promptly notified of any apparent conflict between the Government's proprietary interests and those of others.

The U.S. Government is absolved from any litigation which may ensue from the contractor's infringing on the foreign patent rights which may be involved.

WADC TECHNICAL REPORT 52-59

STUDIES ON BURNER FLAMES OF HYDROGEN-OXYGEN MIXTURES AT HIGH PRESSURES

Rudolph Edse
Flight Research Laboratory

April 1952

RDO No. R-467-1

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

McGregor & Werner, Inc.
Dayton, O. 100, 16 June 52

FOREWORD

This report was prepared by Dr. Rudolph Edse on work done at the Ohio State University while he was a member of the Flight Research Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, with Lt R. H. Murray acting as project engineer. The work may be identified under RDO number R-467-1 entitled, "Mechanism and Kinetics of Hydrogen Combustion."

This is the final and concluding report.

ABSTRACT

A new apparatus for the study of bunsen burner flames at pressures up to 100 atmospheres is described. With hydrogen-oxygen mixtures the flames at elevated pressures are always turbulent unless burner tubes with an inner diameter much smaller than 0.03 cm are used. The flash-back conditions of turbulent hydrogen-oxygen flames at atmospheric pressure and at 14.6 atmospheres are given by the critical velocity gradient at the wall of the burner tube. The temperature of the burner tip has a large effect on the flash-back tendency of the flame. For turbulent flames the critical flash-back gradient is larger than for laminar flames. The limit between stable flame and flash-back was found to be very sharp. From measurements of the flame pressures and from photographs of the flame cones it is concluded that the burning velocity of turbulent flames is not larger than that of laminar flames. Depending on the mixture ratio the burning velocities of hydrogen-oxygen flames at 14.6 atmospheres are 2 to 3 times as large as those of atmospheric flames. From a theoretical consideration it is concluded that the burning velocities of hydrogen-oxygen flames increase with pressure because the flame temperatures increase with pressure, and thus also the heat conduction from the burning zone into the unburned gas.

The intensity of the emission spectrum of hydrogen-oxygen flames recorded with a 21 ft. grating spectrograph is greatly increased with pressure. The iso-intensity method is used for the measurement of flame temperatures.

PUBLICATION REVIEW

Manuscript Copy of this report has been reviewed and found satisfactory for publication.

FOR THE COMMANDING GENERAL:

Leslie B. Williams

LESLIE B. WILLIAMS
Lt. Col., USAF
Chief, Flight Research Laboratory
Research Division

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS

INTRODUCTION

As part of an extended program of flame studies, an apparatus has been built for the investigation of steady burner flames at high pressures.

High pressure flames are of great technical interest since they occur in the engines of most prime movers of the present time. Our knowledge of flame phenomena at high pressures is rather incomplete. The little information that we have is extrapolated from data of experiments at atmospheric pressure, or it is obtained from investigations of explosions in bombs, or in reciprocating engines. It is quite difficult to evaluate these experiments because of the short duration of the process which usually does not allow attainment of equilibrium conditions. Moreover, these processes take place at constant volume whereas for the measurements of flame velocities and the investigation of reaction mechanisms a process at constant pressure is preferable.

A thorough understanding of such effects as pressure and additives on flame velocity will have some significant influence on the design of internal combustion engines and the preparation of motor fuels. With the trend towards higher compression ratios in internal combustion engines the problem of knocking once more has become one of extreme importance. Rather than 'reinforcing' the unburnt gasoline-air mixture by adding tetraethyl lead to prevent ignition of the unburnt gas before the normal flame front has traveled through the mixture, it might prove more successful to look for means to increase the flame velocity of gasoline-air mixtures to such values, that a smooth combustion process is accomplished even at highest engine speeds in the time that it takes the piston to move from upper dead center to the point where the exhaust valve begins to open. The advantage of such fuel mixtures is obvious, particularly when rapidly burning lean fuel-air mixtures could be found. No spark advance is necessary and the problem of knocking is eliminated.

A great number of papers [2)] has been published on the measurements of flame velocities at atmospheric pressure and below; and data for flame velocities of a large variety of air-fuel or oxygen-fuel combinations are available. However,

the effect of high pressure on flame velocity or reaction mechanism is not known. The effect of a moderate increase in pressure was studied by several authors [3]. Ubbelohde and Koelliker found that a mixture of carbon monoxide with air has a flame velocity of 24 cm/sec at 4 atmospheres whereas the same mixture has a flame velocity of 42 cm/sec at atmospheric pressure. Similar results were found with methane-air mixtures. However, inconsistent results were obtained for hydrogen-air mixtures; in a burner tube of 0.95 mm inner diameter the flame velocity was found to increase with increasing pressure whereas in a burner tube of 2.00 mm diameter the flame velocity was not affected by pressure.

Investigations that deal with the reaction mechanism of combustion processes occurring at high pressure are conspicuously lacking. Studies of the combustion phenomena of solid propellants [4] for rockets indicate that the reaction mechanism at high pressures is entirely different from that at normal pressure. Whether such conditions exist also in gaseous oxidant-fuel mixtures is not known.

The apparatus described in this paper is planned for the measurement of burning velocities of hydrogen-oxygen flames and for the study of the effect of additives on the flame velocities both over a range of pressures up to 100 atmospheres. The apparatus is also intended for the study of the emission and absorption spectra of pressurized flame gases.

The first experiments with the new apparatus showed that at high pressures the flow of the hydrogen-oxygen mixtures in the burner tube is turbulent even when tubes with an inner diameter of 0.03 cm are used. The reason for this behavior is the increase of Reynolds number with pressure and the high flame velocities of hydrogen-oxygen mixtures. Therefore, great difficulties were encountered in obtaining stable hydrogen-oxygen flames at elevated pressure. The present theories on the stability of burner flames [5] are not applicable to turbulent flames and they do not discuss the effect of pressure. To fill this gap the conditions for flash-back of turbulent flames at atmospheric and elevated pressure were studied. The conditions for blow-off of turbulent flames have been investigated by Bollinger and Williams [6].

APPARATUS

The floor plan of the apparatus for the study of high pressure flame phenomena is given in Fig. 1. The section of the room which is occupied by the combustion chamber for the pressurized burner flames is separated by a 3/8 inch steel wall and roof from the section that contains the control panel and the spectrograph. The flames are observed through holes in this partition and through quartz windows in the chamber by means of mirrors and a telescope. The control panel is shown in Fig. 2 and the combustion chamber is pictured in Fig. 3. A diagram of the apparatus is given in Fig. 4. All gases are taken from standard tanks with an initial pressure of approximately 150 atmospheres. By means of a Grove Powreactor Dome Controller (DC, Fig. 4) this pressure is reduced to a constant working pressure of 40 to 100 atmospheres depending on the chamber pressure desired. The working pressure is indicated by an Ashcroft Duragauge (M_2) with a 6 inch dial. The volume flows of the gases are adjusted and controlled by the combination of a Grove High Pressure Regulator (HPR), a needle valve (V_2) and a Grove Back pressure Regulator (BR_H). The delivered pressure of the back pressure regulator is set just a little above the desired chamber pressure. In this way any change of pressure in the downstream section does not affect the rate of the gas flow and it is possible to maintain constant flow rates of all gases during several hours. The gases are metered at high pressure by measuring the pressure drop that they experience when they pass through a cotton plug in a copper tube (F). These flow meters are calibrated by the displacement method for flows up to 100 cm^3/sec NPT and by comparison with a wet testmeter for larger volume flows. From time to time the flowmeters are recalibrated. According to these checks the plugs do not change. After hydrogen and oxygen have been metered they are mixed in a small mixing tube (MT). The 1/8 inch copper tubing from the mixing tube to the burner has a length of 200 to 1000 diameters of the burner tubes. The mixing tube is water cooled to prevent its burning out when the flames flash back. The construction of the burner used in the experiments at high pressures can be seen in Fig. 5. The combustion chamber consists of a cold drawn steel pipe with an inner diameter of 7 inches and a length of 20 inches. The wall thickness is 1/2 inch. The 1 1/4 inch bottom is welded into

the pipe whereas the 1 1/4 inch top plate is bolted by 12 one inch machine bolts to a 1 1/4 inch flange welded around the chamber. A gas tight seal is obtained by placing a rubber O-ring between lid and flange. The burner is inserted into the chamber through a one inch opening in the bottom. The burner flange is bolted to the bottom and sealed with an O-ring. Two quartz windows 1/2 inch thick and 1 inch in diameter are mounted on opposite sides of the chamber. To prevent condensation of water vapor from the flame gases on these windows, they are equipped with a defroster (Fig. 6). The pressurizing gas enters the chamber through the defrosters and a steady flow of 100 to 200 cm^3/sec of gas is passed through the chamber continuously. The window frames also accept 6 x 1 x 1 inch glass plates. However, it is very difficult to prevent condensation on these large windows. The upper section and the lid of the combustion chamber are cooled by running water (Figs. 3 and 4). The exhaust gas leaving the chamber at the top is freed from moisture in a cooling coil (C). The condensate is collected in a trap (T) from which it can be drained (V_3). The water condensing in the chamber is removed through a valve (V_4) in the bottom after each experiment. The pressure in the chamber is indicated by an Ashcroft Duragauge (Pc) with a 6 inch dial. A Grove Airdome Back Pressure Regulator (BRc) is used to maintain constant pressure in the chamber, however, only a small fraction of the exhaust gas is expanded through this regulator into the atmosphere. Most of the exhaust gas is passed through a normal two stage regulator (R). The flow rate of the exhaust gas is measured with a Fisher and Porter Flowrator (FR). The flames are photographed with a 4x5 view camera, whose 6 inch lens is brought as close to the window of the chamber as possible. Under this condition the image of the flame on the negative is about 2.5 times normal size. A small electric bulb inside the combustion chamber is used for the illumination of the tip of the burner tube and of a stainless scale beside the flame. A retractable ignition device serves for the ignition of the hydrogen gas issuing from the burner tube. The igniter consists of an electrically heated platinum wire mounted on a piston which is pneumatically operated. The combustion chamber is anchored on a sturdy iron frame so that an image of the flame cone can be projected through one of the quartz windows on the slit of a 21 ft. grating spectrograph.

EXPERIMENTAL

In the early experiments the flames were started at atmospheric pressure to eliminate any possibility of an explosion. For this purpose the burner was disconnected from the chamber and the hydrogen-oxygen mixture issuing from the burner tube was ignited outside the chamber. Then the burner with flame was inserted into the chamber while the pressurizing gas was passed through the chamber. The flow rates of hydrogen and oxygen were adjusted so that at atmospheric pressure the flame was near its blow-off limit. This procedure was necessary to prevent flash-back during the first rise of pressure. The chamber pressure was increased very slowly by throttling the exhaust gas with the two stage regulator (R). At the same time the flow rates of hydrogen and oxygen were increased in such a fashion that the mixture ratio was changed as little as possible. When the conditions for flash-back were reached, the flames flashed back without showing any specific change in their structure before they actually disappeared. Except for very rich mixtures flash-back was always instantaneous and always resulted in detonation of the hydrogen-oxygen mixture in the mixing tube and in the line from the burner to the mixing tube. These detonations were very violent, particularly at the higher chamber pressures. Usually the copper tubing was ruptured by these detonations. A few attempts were made to suppress or arrest the detonation, however, all devices that were used proved ineffective. The shock waves went through a series of 0.03 cm holes which were interspaced with heavy walled tubing with an inner diameter of 2 inches and a length of 1 inch. They also passed through 1/4 inch copper tubes which were packed with copper shavings. Although at atmospheric pressure the flames were quenched in a copper tube with an inner diameter of 0.13 cm, at elevated pressures they traveled through a tube with an inner diameter of 0.03 cm. Even reduction of the length of the connecting tubing did not eliminate the detonations since at high pressures the transition from normal flames to detonation occurs after the flames have traveled only a few centimeters in the tube (Fig. 7). The measurements of the linear gas velocities in the burner tubes at flash-back as a function of pressure were extremely tedious because of the unpredictable flash-back conditions of these flames and because all flames had to be carried through all stages from atmospheric pressure on up to higher pressures.

The reproducibility of the flash-back points was greatly affected by the length of time in which the flash-back was reached. Many times a 'stable' flame flashed back after it had burned for several minutes and absolutely no change in the gas flows or in chamber pressure had occurred. This behavior of the flames explains the large scattering of the points of measurement in Fig. 8 where the gas velocities at flash-back are plotted against pressure in the combustion chamber. Table 1 contains the data of these experiments. It is true that a small amount of scattering was introduced by variations in the mixture ratio. However, in the region from 60 to 70 percent hydrogen this effect is small as can be seen in Fig. 10. A few experiments were carried out with hydrogen-air mixtures. The results are given in Table 2 and Fig. 9. At pressures above 15 atmospheres the critical flash-back velocities of these flames were found to decrease with rising pressure which is in contrast to the behavior of hydrogen-oxygen flames. The flash-back of apparently stable flames was observed also in many later experiments including flames at atmospheric pressure (Fig. 26). It was assumed that this erratic behavior is caused by an increase in temperature of the burner rim. This assumption proved to be right for it was found later that the conditions for flash-back are extremely reproducible when water cooled copper tubes were used as burners. In the experiments at high pressure, however, no water cooled tubes were used. The scattering of the points of measurement could be reduced greatly by using heavy walled copper tubes. In this way a more uniform and lower temperature of the burner mouth was provided which led to lower flash-back velocities as can be seen in Fig. 10. The solid curve of this graph represents the velocity gradients of the gas flows at the burner wall for flash-back of hydrogen-oxygen flames burning at a pressure of 14.6 atmospheres in a straight monel tube which was encased in a silver jacket. The procedure used in carrying out the experiments represented in Fig. 10 and Tables 3, 4, and 5 was quite different from the earlier method. After the chamber was pressurized with nitrogen the flame was started by igniting a stream of hydrogen without any admixture of oxygen in a concentric stream of air (Fig. 5). The hydrogen was ignited by an electrically heated platinum wire which was quickly withdrawn as soon as the hydrogen burned. The flow of hydrogen was then adjusted to a desired value before oxygen was added to it. When the hydrogen-oxygen flame appeared sufficiently stable the concentric stream of air was replaced

by nitrogen so that the hydrogen-oxygen flames were burning in an atmosphere of nitrogen. A large number of the experiments represented in Fig. 10 were carried out with oxygen as the ambient gas and a few flames were burned in helium. It was found that the nature of the chamber gas did not affect the flash-back conditions. The flash-back points were obtained by increasing the flow rate of oxygen without changing that of hydrogen in cases where the flow of hydrogen was below a critical value above which no flash-back occurs for any mixture ratio. This procedure yields the flash-back velocities for rich mixtures. The points for lean mixtures were obtained by starting with very lean mixtures and then increasing the flow rate of hydrogen. Fig. 10 and Table 4 show also the results that were obtained with a larger burner. However, only very rich mixtures could be studied with this burner tube because mixtures near the stoichiometric point required hydrogen flows which resulted in flames that delivered too much heat to be handled safely in the present combustion chamber.

The evaluation of the measurements on the stability of high pressure flames is complicated by the fact that pressure is not the only new parameter in these experiments; the flames are also turbulent as it is evidenced by the Reynolds numbers that were calculated for the flows of the gas mixtures in the burner tubes. Therefore, the conditions which lead to flash-back of turbulent flames burning at atmospheric pressure were established first. The same apparatus was used for these experiments, however, the lid of the combustion chamber was removed. The diameters of the burner tubes ranged from 0.122 cm to 1.031. The complete data of all tubes are compiled in Table 14. The experiments were executed in the same way as the measurements of flash-back at elevated pressure. Flash-back was always instantaneous and the flames near the flash-back limit differed in no way from stable flames. No tilted flames or partial entrance of the flames into the tube were observed. The results of these measurements are compiled in Tables 6, 7, 8, 9, 10, 11, 12, and 13 and in Figs. 11, 12, 13, 14, 15, and 16. The flash-back points were easily reproducible in all burner tubes. The effect of temperature of the burner rim on flash-back was apparent from the enormous increase of flash-back velocity with burner diameter. Evidence for this effect was obtained when much lower flash-back velocities were found by igniting

a jet of a mixture of hydrogen and oxygen issuing from the burner port. The resulting flames usually flashed back after a few seconds because of the heating of the burner tube by the flame. The flash-back velocities determined in this way are marked by an asterisk in the tables. The values are still higher than those obtained in water cooled copper tubes because of the back pressure created by the flame. A few experiments were also carried out with laminar flames. The results of these measurements differ somewhat from those obtained by Lewis and von Elbe [5] as can be seen in Table 6 and Fig. 11. The critical velocity gradients for flash-back determined in the present investigation are lower than the values that were published by Lewis and von Elbe. The discrepancy exists only for the hotter flames. Also contrary to their observation it was found that the limit between flash-back and stable flame is very sharp and that the critical velocity gradient for flash-back does not increase for larger Reynolds numbers as long as the flame is really laminar. Even at Reynolds numbers around 3000 laminar flames were observed as it was evidenced by schlieren photographs of the flames. The critical velocity gradients for flash-back of these flames do not differ from those observed in smaller tubes (compare Table 7 and Fig. 12 with Table 6 and Fig. 11). The larger critical velocity gradients and the regions of partial entrance of the flame cones into the burner tubes as observed by Lewis and von Elbe are probable the result of an increase of the temperature of the burner rim with increasing diameter of the burner tube. Lewis and von Elbe used water cooled pyrex tubes whereas water cooled copper tubes served as burner tubes in the present investigation. Photographs of flames that are near the flash-back limit are shown in Figs. 27 and 28.

The burning velocities of the flames were derived from photographs of the flames by measuring the angle of the inner flame cone as it appears at the rim of the burner tube (Fig. 29). The cones obtained in this way are larger than the actual flame cones in the case of turbulent flames but they are identical with the true flame cones of laminar flames on nozzles. From these cones the flame velocities were calculated according to the equation

$$U_F = \frac{\overline{U_G}}{\sqrt{4\left(\frac{h}{d}\right)^2 + 1}} \qquad (1)$$

It is realized that for a correct determination of flame velocities the relationship $U_F = \frac{V_G}{S_F}$ has to be evaluated. (However, the measurement of true flame velocities does not lie within the scope of this paper.) The values needed for the study of the effect of pressure on flame velocity are primarily intended for comparison. The results are graphically depicted in Figs. 18 and 19 and for 14.6 atmospheres they are also tabulated along with other pertinent data in Table 15. The higher values obtained with the convergent nozzles agree with the observations of Mache and Hebra [7]. It was found that the size of the inner cone of the flame recorded photographically depends on the sensitivity range of the emulsion. Different flame velocities (Fig. 18) were obtained for the same flame when it was photographed on infrared plates (Kodak type I - L) one through a red filter (Wratten 25 A) and the other through a blue filter (Wratten C-5). All other flame photographs were made on panchromatic films. Photographs of high pressure flames are shown in Figs. 30 to 37 whereas Figs. 38 to 41 depict flames on a burner tube of the same diameter at atmospheric pressure.

DISCUSSION:

Following the theory which was developed by Lewis and von Elbe [5] for laminar flames an attempt was made to relate flash-back of turbulent flames to the velocity gradient of the gas flow at the wall of the burner tube. According to the theory on turbulent gas flows in tubes, the flow in a very thin layer adjacent to the wall of the tube is laminar. The linear velocity of the gas in this laminar boundary layer increases linearly with the distance from the wall (Fig. 17) and is given by the expression [8]

$$U = \frac{0.0392}{R_e^{\frac{1}{4}}} \frac{\bar{U}_G^{\,2}}{\nu} x \tag{2}$$

with $0 \leq x \leq \delta$. The velocity gradient at the wall is derived from this equation by differentiation to x

$$\frac{du}{dx} = g^t = \frac{0.0392}{R_e^{\frac{1}{4}}} \frac{\bar{U}_G^{\,2}}{\nu} \tag{3}$$

Disregarding the small effect of pressure on the dynamic viscosity we can write for the kinematic viscosity

$$\nu = \frac{\nu_o}{p} \qquad (4)$$

and substituting this expression into equation (3) we obtain for the velocity gradient at the tube wall when the flow in the tube is turbulent

$$g^t = \frac{0.0392}{R_e^{\frac{1}{4}}} \frac{\overline{U}_G^{\,2}}{\nu_o} p \qquad (5)$$

The velocity distribution from δ to the center of the tube (Fig. 17) is given by the expression

$$U = 1.235\overline{U}_G\left(\frac{x}{\frac{d}{2}}\right)^{1/7} \qquad (6)$$

with $\delta \leq x \leq \frac{d}{2}$. Equations (2), (5), and (6) hold for straight tubes whose lengths are about 50 times their inner diameters. When the ratio of tube length to diameter is less than 50 or when the tube is slightly convergent the velocity profile is much flatter, and the velocity gradient at the wall is larger than in a long straight tube, whereas in a divergent tube the profile is steeper and the velocity gradient at the wall is smaller than in a straight tube. A small number of experiments carried out in divergent or convergent burner tubes did not bear out these rules (Table 15). It is believed that the lack of water cooling these tubes is responsible for this behavior. More experiments are necessary to elucidate the effect of tube shape on the stability of flames. The velocity gradients at the wall of the burner tube were calculated according to equation (5) for the conditions of flash-back of the flames (Tables 1 to 13). These critical velocity gradients for flash-back were plotted as a function of mixture ratio for each burner tube (Figs. 10 to 15). The results show that for uncooled burner tubes the critical velocity gradients for flash-back increase rapidly with the diameter of the burner tube. However, when water-cooled burners were used the critical flash-back gradients were found to be independent of tube diameter. The critical velocity gradient as given in equation (5), therefore,

represents a true criterion for flash-back of turbulent flames. From the equations for the critical velocity gradients we can calculate the minimum volume flow that is necessary to obtain stable flames once the critical velocity gradient g has been determined. When the flow of the gas mixture in the tube is laminar this minimum flow rate is derived from the expression [5]

$$V^{min} = \frac{\pi d^3 g_F^{\ell}}{32} \qquad (7)$$

and when the flow is turbulent it is calculated from the equation

$$V_o^{min} = 5.\ d^{15/7} \cdot \left(p/p_o\right)^{8/7} \nu_o^{\ 3/7} \left(\frac{g_F}{p/p_o}\right)^{4/7} \qquad (8)$$

Larger flow rates are necessary to prevent flash-back when the burner tubes are not efficiently cooled. Without cooling, the rim of larger burners is heated more than that of smaller tubes because for equal velocity gradients the mass flow of gas through the burner tube and thus the heat generated by the flame is proportional to the third power of the tube diameter in case of laminar flames and proportional to the 2-1/7 power in case of turbulent flames whereas for tubes of equal wall thickness the heat can be conducted only through an annulus whose area is proportional to the diameter of the tube. With increasing temperature of the burner rim the depth of penetration of the quenching of the reactions in the flame by the burner wall is reduced [9]. Consequently the velocity gradient has to be larger to prevent the flame from flashing back into the burner tube. With reference to Fig. 25 we can write

$$g_F = \frac{U_F}{x} \qquad (9)$$

assuming that at the point of contact of the curves of flame velocity and gas velocity the flame velocity has still its normal value U_F. According to equation (8) the critical velocity gradient for flash-back might be expected to be the same for laminar and turbulent flames when the flame velocity, U_F, and the quenching distance, x, are the same. However, the measurements of flash-back clearly indicate that g_F^t is larger than g_F^{ℓ} (Fig. 16). This result seems to be in agreement with

the theory that the flame velocity of turbulent flames is larger than that of laminar flames [10]. According to our measurements of the flame velocities of turbulent hydrogen-oxygen flames it was found that, within the accuracy of measurement, the flame velocity in case of turbulence is the same as that of laminar gas flows in the burner tube. The results of our measurements are represented in Figs. 18 and 19. It is believed that our method of deriving the flame velocities from photographs of the flames is correct, particularly with regard to the flash back conditions since all turbulent flames have a laminar flame zone at the lower part of the flame cone. The conditions at this section of the flame are of primary importance for the phenomena of flash-back. According to the definition of flame velocity

$$U_F = \frac{V_G}{S_F}$$

it is impossible to derive flame velocities of turbulent flames from geometrical measurements of the flame cone since the true surface of the flame front cannot be obtained from the dimensions of the flame cone which has a very thick and poorly defined flame zone (Fig. 42). The assumption that the flame velocities of turbulent hydrogen-oxygen flames are not different from those of the laminar flames is supported by our measurements of the flame pressure of turbulent hydrogen-oxygen flames. It was found that the flame pressure of the turbulent flames is not larger than that of the laminar flames (Fig. 24). The curve of Fig. 24 was calculated according to an expression given by Mache [11]

$$p_F = p \frac{M_u}{RT_u} U_F^2 \left(\frac{T_F}{T_u} \frac{n_F}{n_u} - 1 \right) \qquad (10)$$

The temperatures of the flames, T_F, and the change of number of moles, $\frac{n_F}{n_u}$ during the combustion were computed for the case that complete chemical equilibrium prevails in the flame gases [12]. For the flame velocities, U_F, the values given in Fig.19 were used. According to this finding, it must be concluded that the difference between g_F^t and g_F^l, is caused by a difference in the quenching distances, x, of laminar and turbulent flames. The increase of g_F^t with pressure (Fig. 16,

note that in this diagram $\frac{g_F^t}{p}$ is plotted) is about proportional to the increase of the flame velocity with pressure (Fig. 19). This observation is in good agreement with the measurements of Friedman and Johnston [9] who found that for propane-air flames the quenching distance is proportional to the minus 0.91 power of the pressure. Since flame velocity is a function of the transport of heat and active particles, like hydrogen atoms, from the reaction zone into the unburnt gas, the question arose whether the effect of pressure on one or both of these quantities could explain the increase of flame velocity of hydrogen-oxygen flames with pressure. For this purpose the temperatures and the compositions of the flame gases of hydrogen-oxygen flames were calculated for atmospheric pressure and for 14.6 atmospheres [12]. The results of these calculations are compiled in Figs. 20, 21, 22, and 23. From these data it must be concluded that the flame velocity of hydrogen-oxygen flames is essentially controlled by the phenomena of heat conduction. The temperatures of the flames are greatly increased with pressure. The effect is larger for mixtures near the stoichiometric point than for lean or rich mixtures. The shape and the position of the maximum values of the curves for the flame temperatures correspond to those of the flame velocities. It is obvious that higher flame temperatures will lead to higher heat flows from the flames zone to the unburnt gas. Diffusion in gases is inversely proportional to pressure. Therefore, the relative concentrations, concentration divided by pressure, of the active particles occurring in hydrogen-oxygen flames are plotted in Fig. 22 in order to show the overall effect of pressure on diffusion of H atoms into the unburnt gas. The position of maximum values of these curves does not agree with that of the flame velocities; moreover, we see that the relative concentrations of all three radicals decreases with increasing pressure. The observation that the flame velocities of hydrogen-oxygen flames increases with pressure therefore is at variance with the theory of Tanford and Pease, which assumes that the flame velocity depends largely on the diffusion of H atoms.

No systematic study of the spectrum of the high pressure flames was carried out. From a few photographs of the emission spectrum it can be concluded that the intensity of the OH spectrum is greatly increased by pressure. Unfortunately, as pressure is increased a very intense continuous spectrum is superimposed on the band spectrum of OH. The origin of this

continuous spectrum is not known but it is probably due to recombination processes such as

$$OH + H = H_2O$$

$$OH + OH = H_2O_2$$

It was hoped to obtain higher vibrational levels for the OH molecule from the spectra of high pressure flames [13] so that an improved value for the dissociation energy of OH could be given. In a stoichiometric H_2-O_2 flame burning at 100 atmospheres, 2.3×10^{13} OH molecules in/cm^3 gas have a vibrational energy that is 100 kcal (approximate dissociation energy of OH) above the ground level. According to Oldenberg's investigations this concentration is sufficient to be detected in absorption when a spectrograph with high resolving power is used, provided that transition probabilities in these high levels are about the same as those in the lower levels. It seems that the photographs of the emission spectrum of the high pressure flames contain a large number of bands which is not found with flames burning at atmospheric pressure. However, no attempt was made to identify these bands as to their origin. The temperatures of the flames were measured spectroscopically by the iso intensity method [1] using the lines of the R_2 branch of the OH band at 3064 Å. The results could not be compared with the calculated temperatures because the exact mixture ratios of H_2 to O_2 were not known. At the time when these experiments were carried out only rich H_2-O_2 mixtures could be burnt in an atmosphere of oxygen which resulted in a very hot outer cone.

BIBLIOGRAPHY

(1) G.H. Dieke and H.M. Crosswhite, Bumblebee Report No. 87, Nov. 1948.

(2) Third Symposium on Combustion and Flame and Explosion Phenomena, in Madison, Wisconsin, Williams and Willkins Baltimore, 1949.
Symposium on Combustion Chemistry, ACS, Cleveland, Ohio, April 9-12, 1951.

(3) W. Jost, Explosion and Combustion Processes in Gases, Translated by H.O. Croft, pp. 89 MacGraw-Hill, New York and London, 1946.

(4) R. Edse, Unpublished Investigation of Combustion of Solid Propellants.

(5) B. Lewis and G. von Elbe, Journ. Chem. Phys. 11 75-97 (1943), 13 89-100 (1945)
K. Wohl, N.M. Kapp, and C. Gazley, see Ref. 2 pp 3
K. Wohl, N.M. Kapp, D.C. Coon, Jr., and R.F. Fulmer, Meteor Report UAC-49 Dec. 1950.

(6) L.M. Bollinger and D.T. Williams, NACA, Technical Note No. 1234, 1947.

(7) H. Mache and A. Hebra, Akademie der Wissenschaften in Wien, Abt IIa Vol. 150 157-174, 1951.

(8) L. Prandtl and O.G. Tietjens, Applied Hydro-and Aeromechanics pp 78. Translated by J.P. Den Hartog, Mac Graw-Hill, New York and London 1934.

(9) R. Friedman and W.C. Johnston, Journ. Appl. Phys. 21 791-795, 1950.

(10) G. Damkohler, Zeitschr. Elektrochem 46 601-626 (1940)
K.I. Shelkin, Journ. Techn. Phys. (USSR) 13 520-530 (1943).
Translated, Techn. Memo. NACA No. 1110, (1947)
D.T. Williams and L.M. Bollinger, see Ref. 2 pp 176
B. Karlovitz, D.W. Denniston, Jr., and F.E. Wells, Journ. Chem. Phys. 19 541-547 (1951).

BIBLIOGRAPHY (Cont'd)

(11) H. Mache, Die Physik der Verbrennungserscheinungen, pp 44, Leipzig 1918.

(12) R. Edse, Air Materiel Command, Progress Report No. IRE - 47 (1946).

(13) R. Edse, see Ref. 2 pp 611.

NOTATION AND DIMENSIONS

d	inner diameter of burner tube	cm
g_F^{ℓ}	velocity gradient at burner wall for laminar gas flow when flame flashes back	$\frac{cm}{sec\ cm}$
g_F^{t}	velocity gradient at burner wall for turbulent gas flow when flame flashes back	$\frac{cm}{sec\ cm}$
h	height of flame cone	cm
ℓ	length of burner tube	cm
M_u	molecular weight of unburnt gas mixture	
n_F	mole number of burnt gas	
n_u	mole number of unburnt gas	
p	pressure in burner tube	atmospheres
p_o	1 atmosphere	
p_c	chamber pressure	atmospheres
p_f	flame pressure	atmospheres
R	universal gas constant, 82.0618	$\frac{lit\ atm}{mole\ deg}$
$R_e = \frac{U_G d}{\nu_o} \frac{p}{p_o}$	Reynolds number of gas flow in burner tube	
S_F	surface of flame front	cm^2
T_F	flame temperature	^oK
T_u	temperature of unburnt gas	^oK

NOTATION AND DIMENSIONS (Cont'd)

U_F	flame velocity (burning velocity)	$\frac{cm}{sec}$
$\bar{U}_G$	average linear velocity of gas mixture in burner tube	$\frac{cm}{sec}$
V_G	volume flow of gas at conditions in burner tube	$\frac{cm^3}{sec}$
V_o	gas flow through burner tube at standard conditions, NPT	$\frac{cm^3}{sec}$
x	quenching distance	cm
ν_o	kinematic viscosity of gas mixture at 1 atmosphere	$\frac{cm^2}{sec}$
δ	thickness of laminar boundary layer	cm

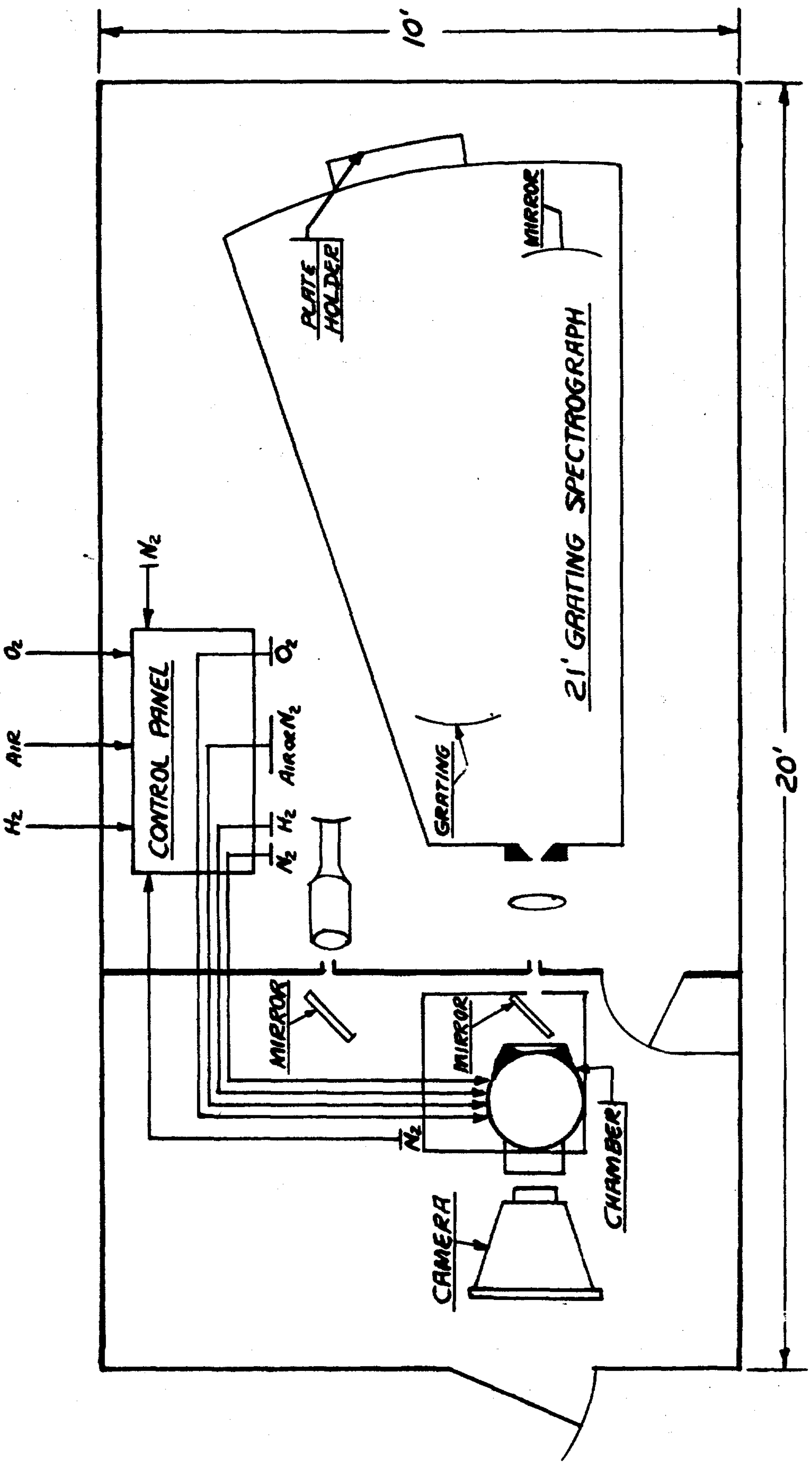


FIG. 1

FLOOR PLAN OF APPARATUS FOR THE STUDY OF HIGH PRESSURE BUNSEN BURNER FLAMES

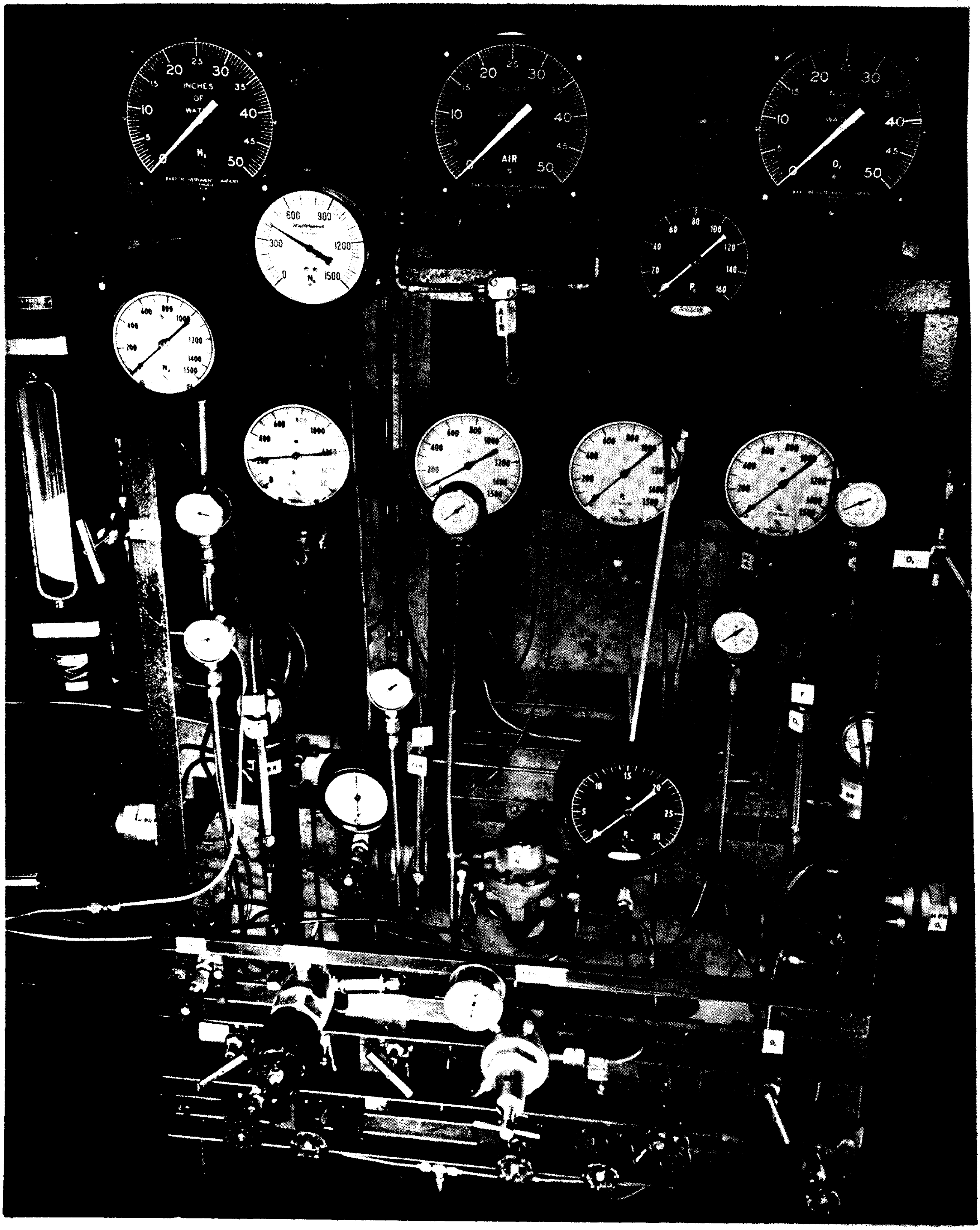


FIG. 2

CONTROL PANEL OF APPARATUS
FOR STUDIES ON HIGH PRESSURE FLAMES

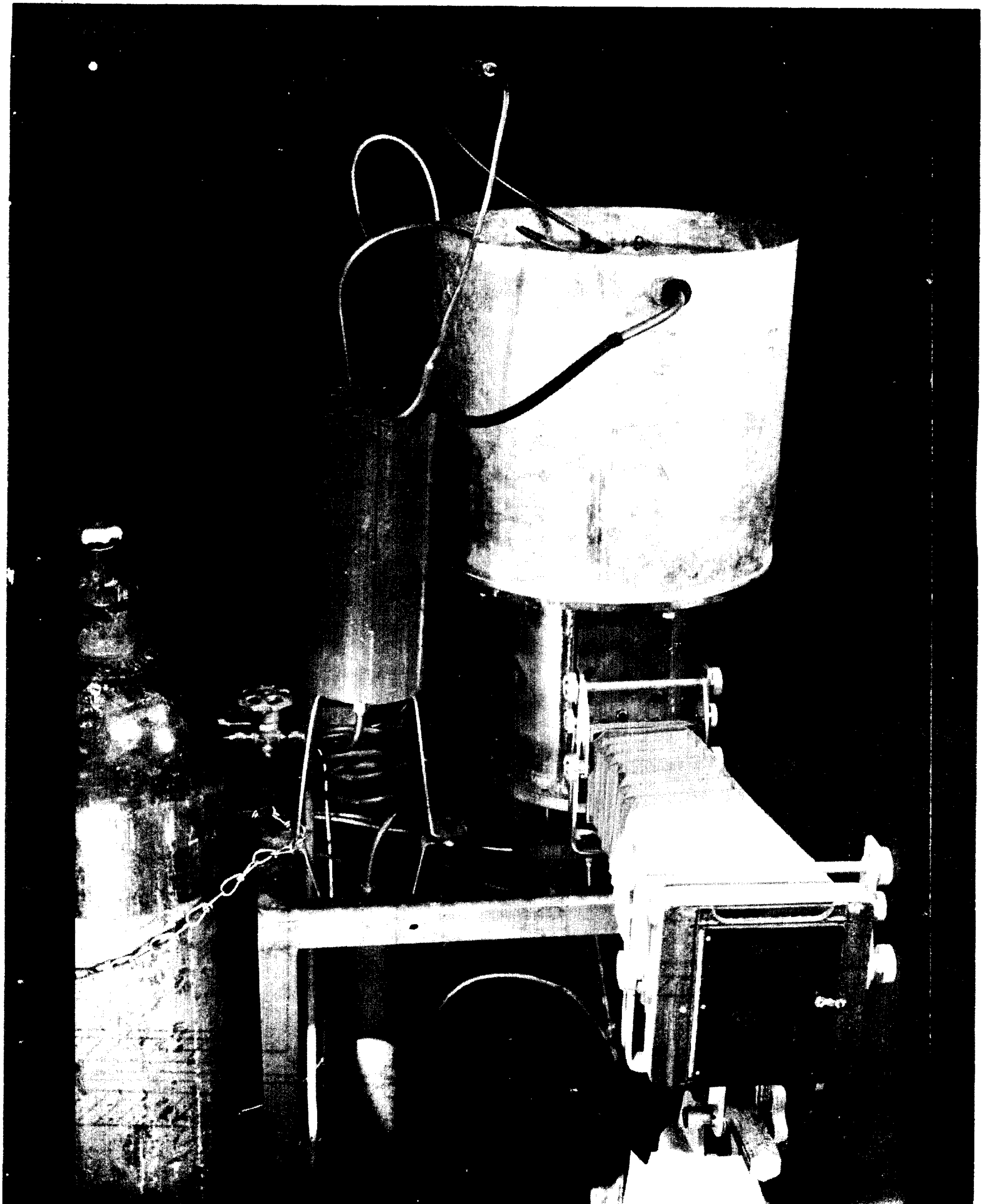


FIG. 3 COMBUSTION CHAMBER OF APPARATUS FOR STUDIES ON HIGH PRESSURE FLAMES

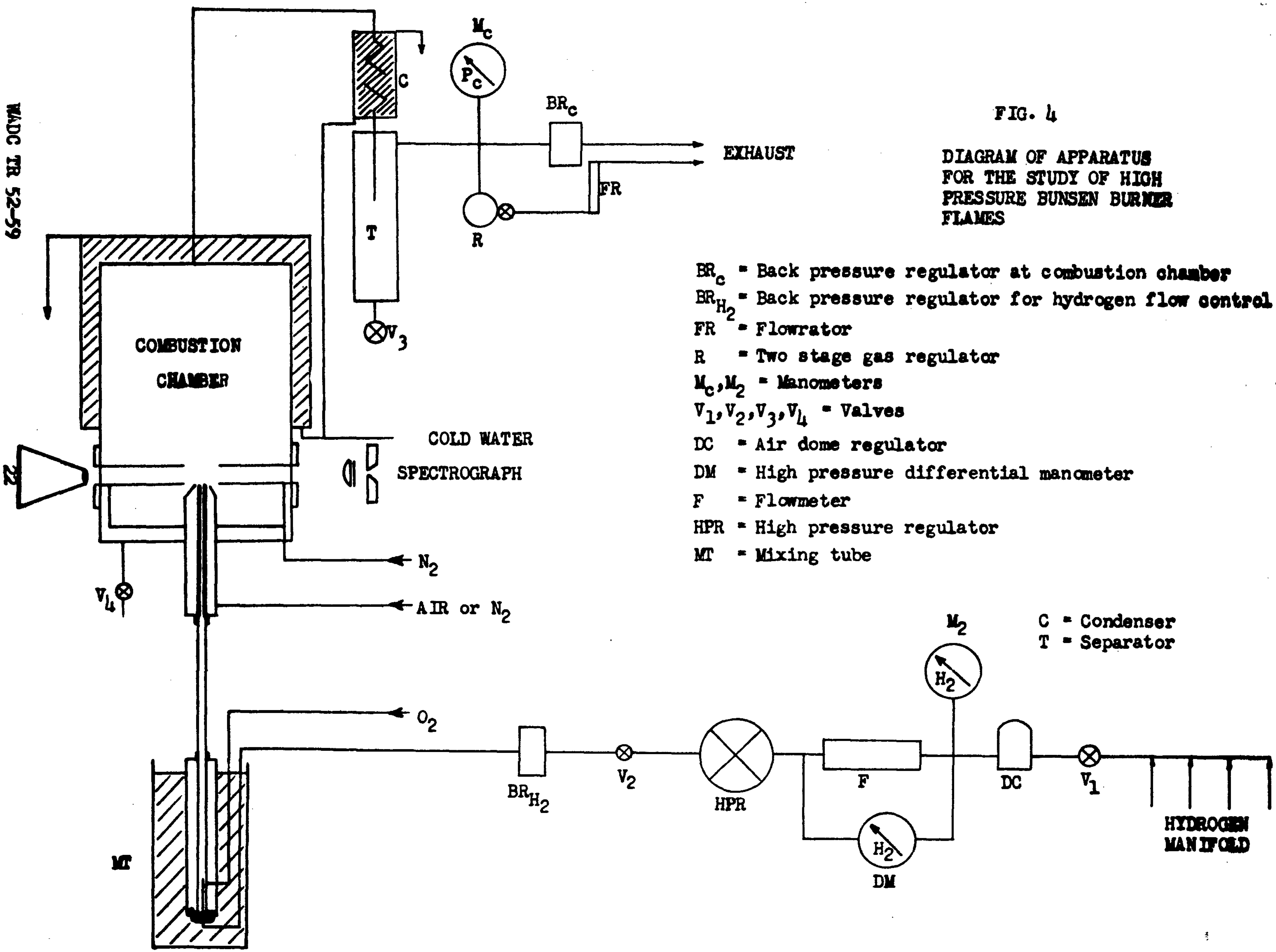


FIG. 4

DIAGRAM OF APPARATUS
FOR THE STUDY OF HIGH
PRESSURE BUNSEN BURNER
FLAMES

BR_c = Back pressure regulator at combustion chamber
BR_{H_2} = Back pressure regulator for hydrogen flow control
FR = Flowrator
R = Two stage gas regulator
M_c, M_2 = Manometers
V_1, V_2, V_3, V_4 = Valves
DC = Air dome regulator
DM = High pressure differential manometer
F = Flowmeter
HPR = High pressure regulator
MT = Mixing tube

C = Condenser
T = Separator

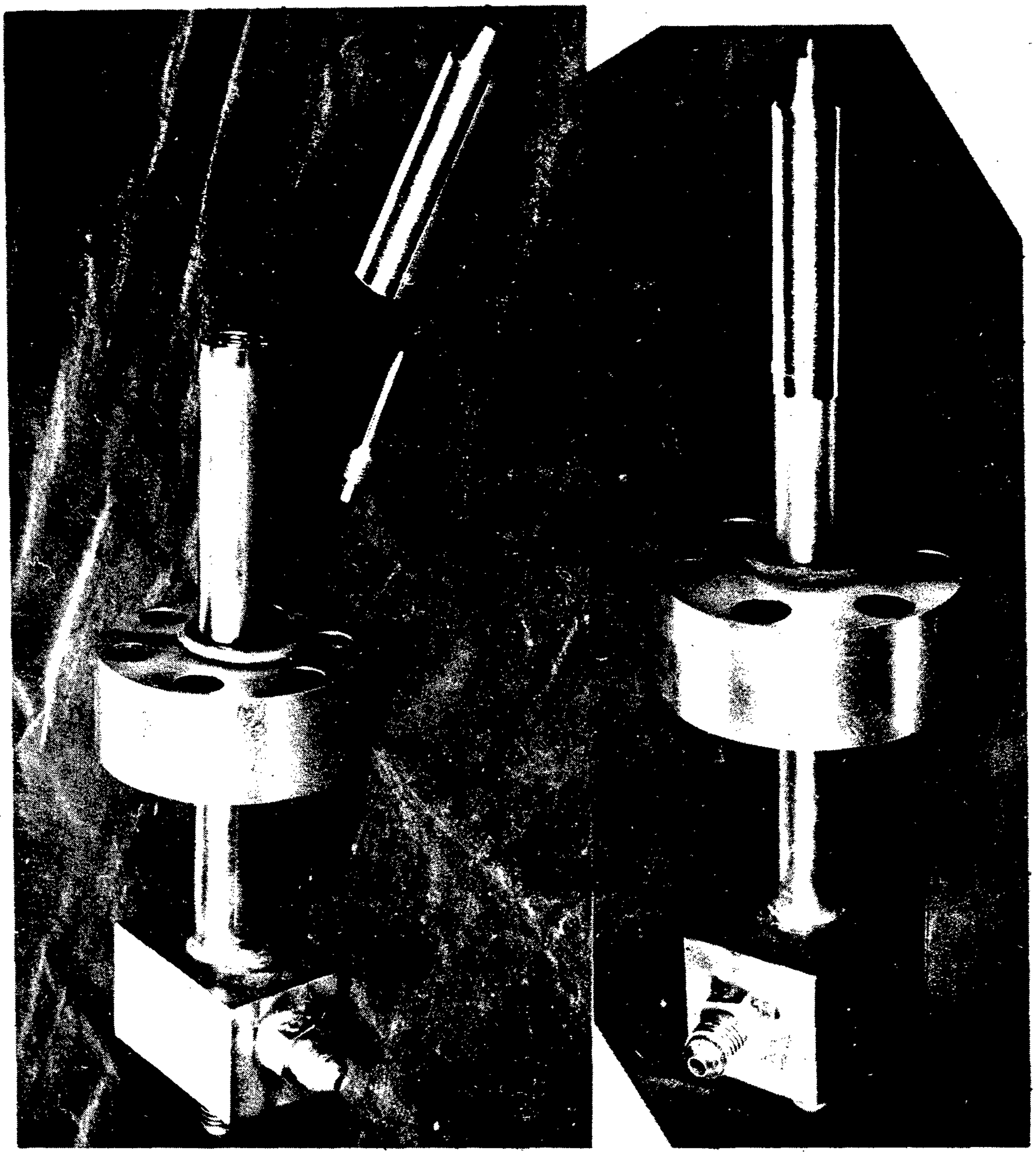


FIG. 5 HIGH PRESSURE BURNER FOR HYDROGEN-OXYGEN FLAMES

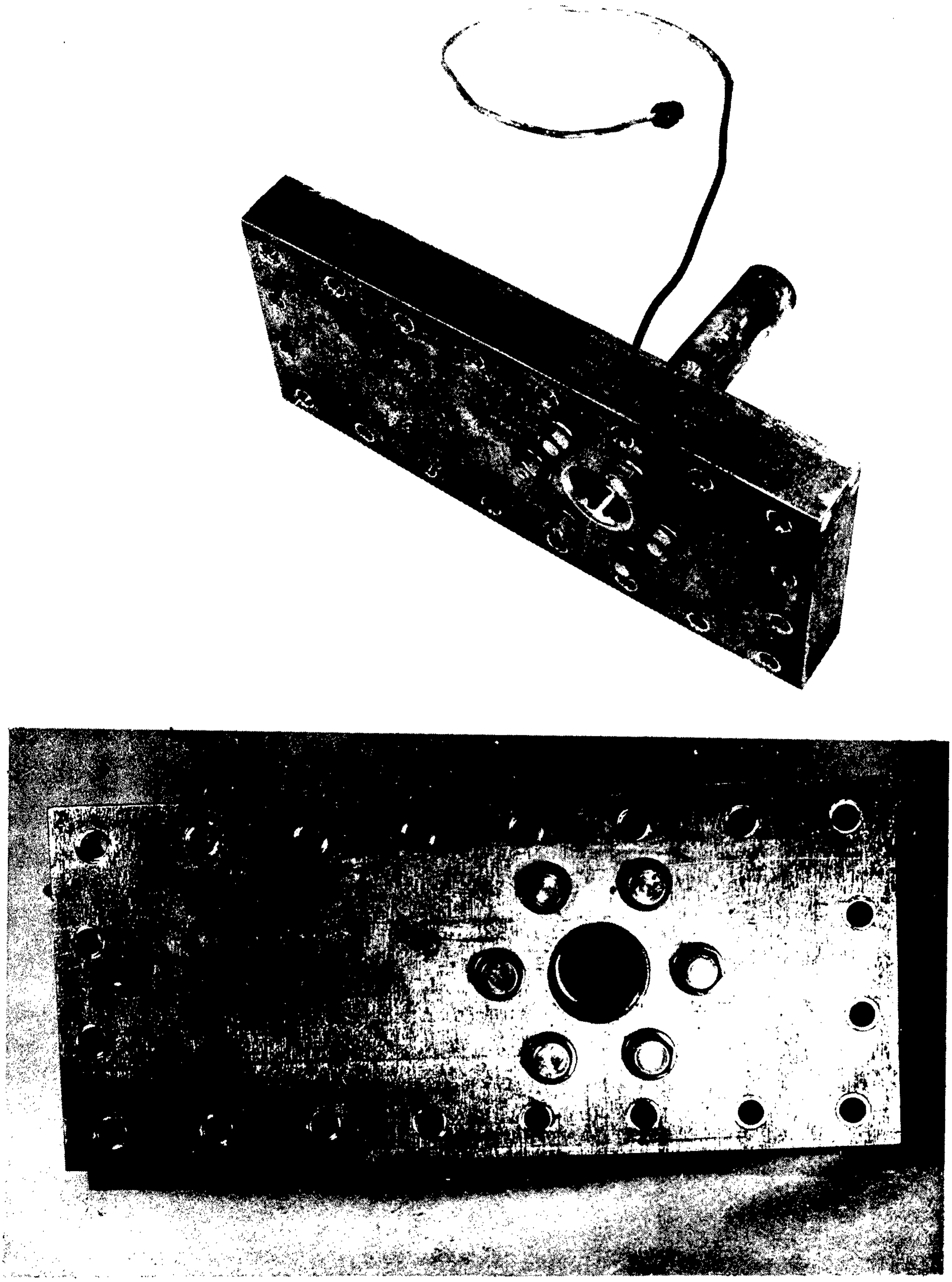


FIG. 6 WINDOW WITH DEFROSTER

NO. 340. M DIETZGEN GRAPH PAPER
MILLIMETER
EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

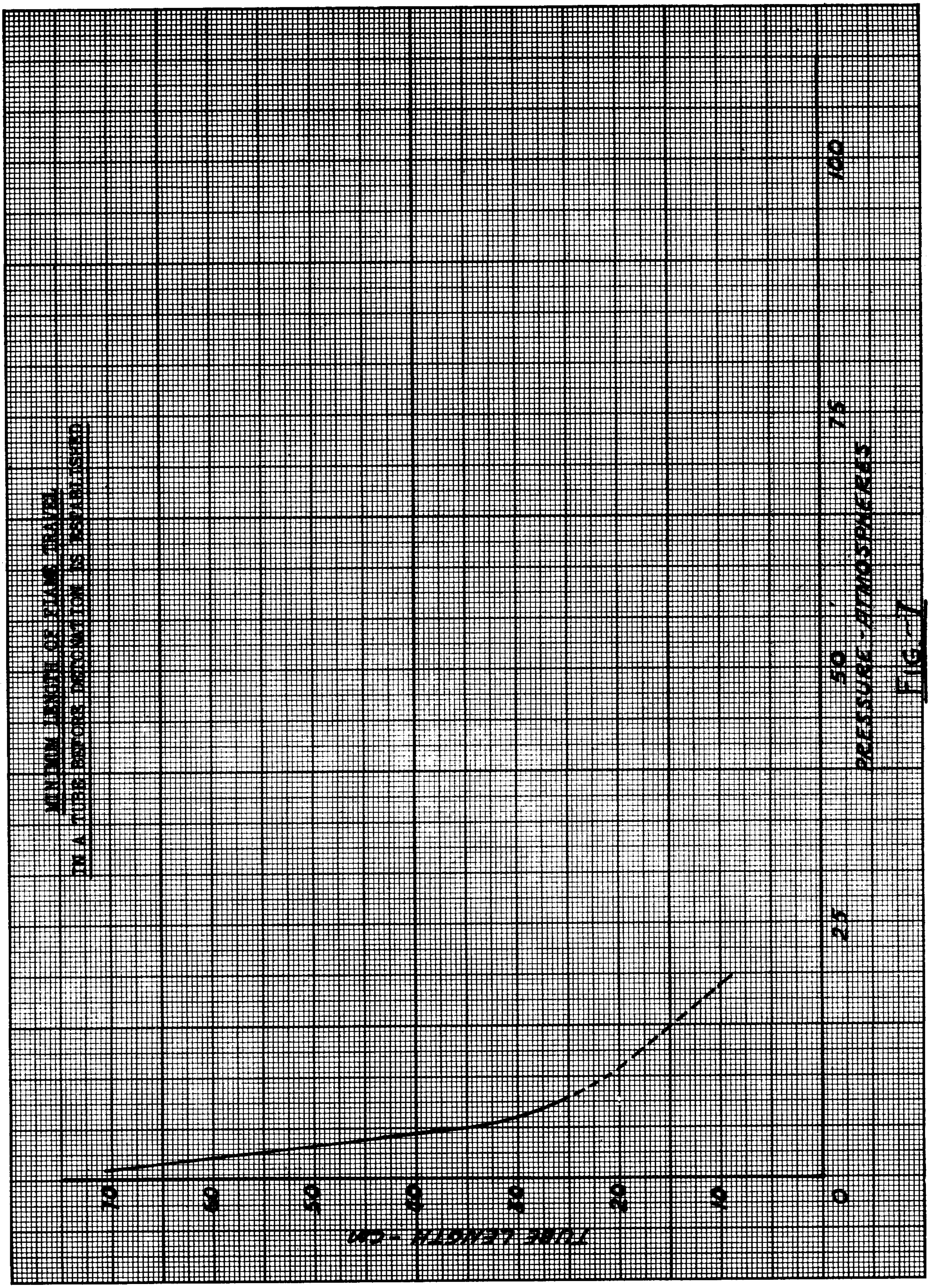
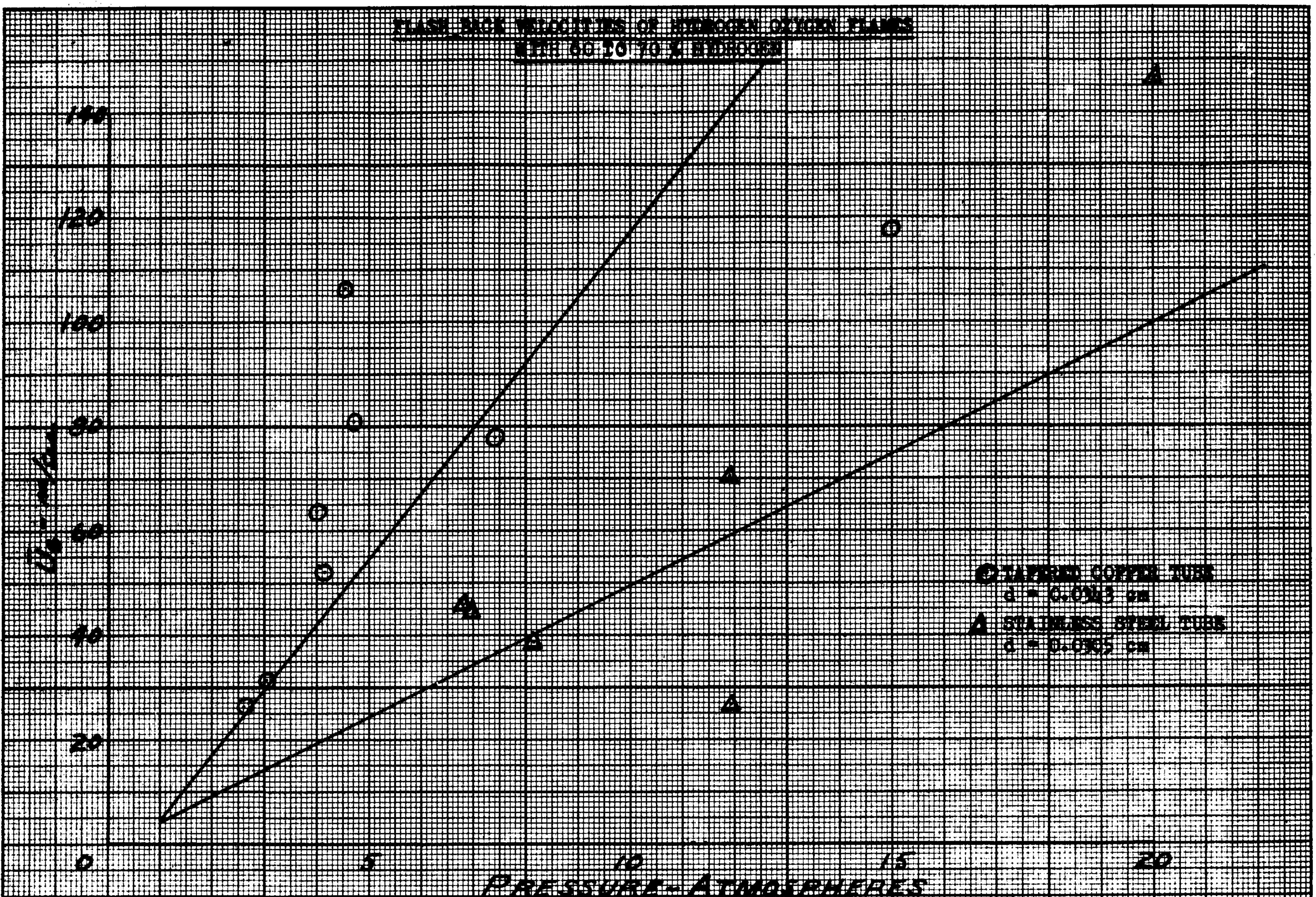


FIG.-7



FLASH BACK VELOCITIES OF HYDROGEN OXYGEN FLAMES
WITH 60 TO 70 % HYDROGEN
140
120
100
80
60
40
20
0
5
10
15
20
PRESSURE-ATMOSPHERES
TAPERED COPPER TUBE
STAINLESS STEEL TUBE

FIG. 8

NO. 340- M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

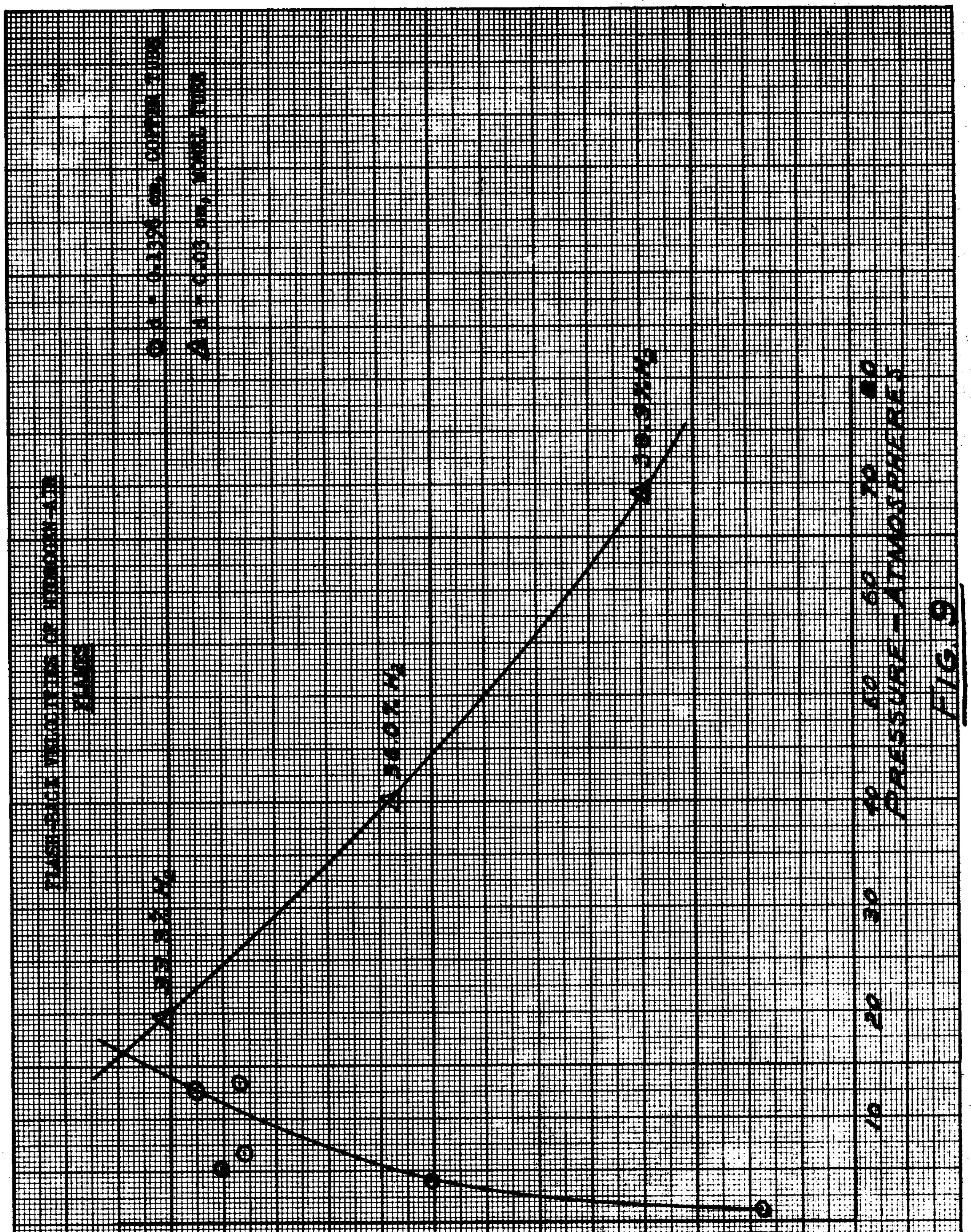


FIG. 9

CRITICAL VELOCITY GRADIENT FOR FLASH-BACK OF TURBULENT

H_2 - O_2 FLAMES AT 14.6 ATMOSPHERES

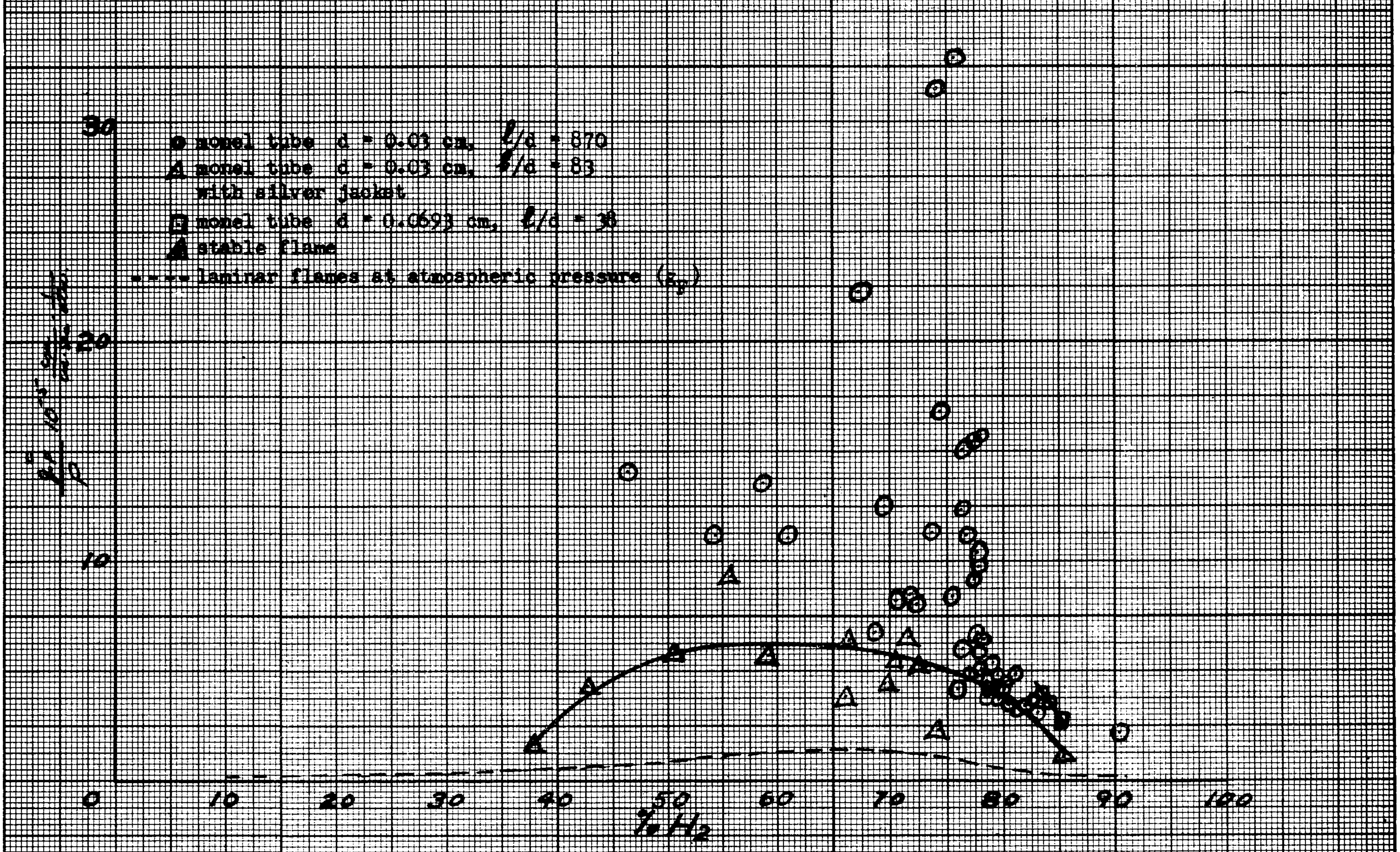


FIG. 10

MILLIMETER

PRINTED IN U. S. A.

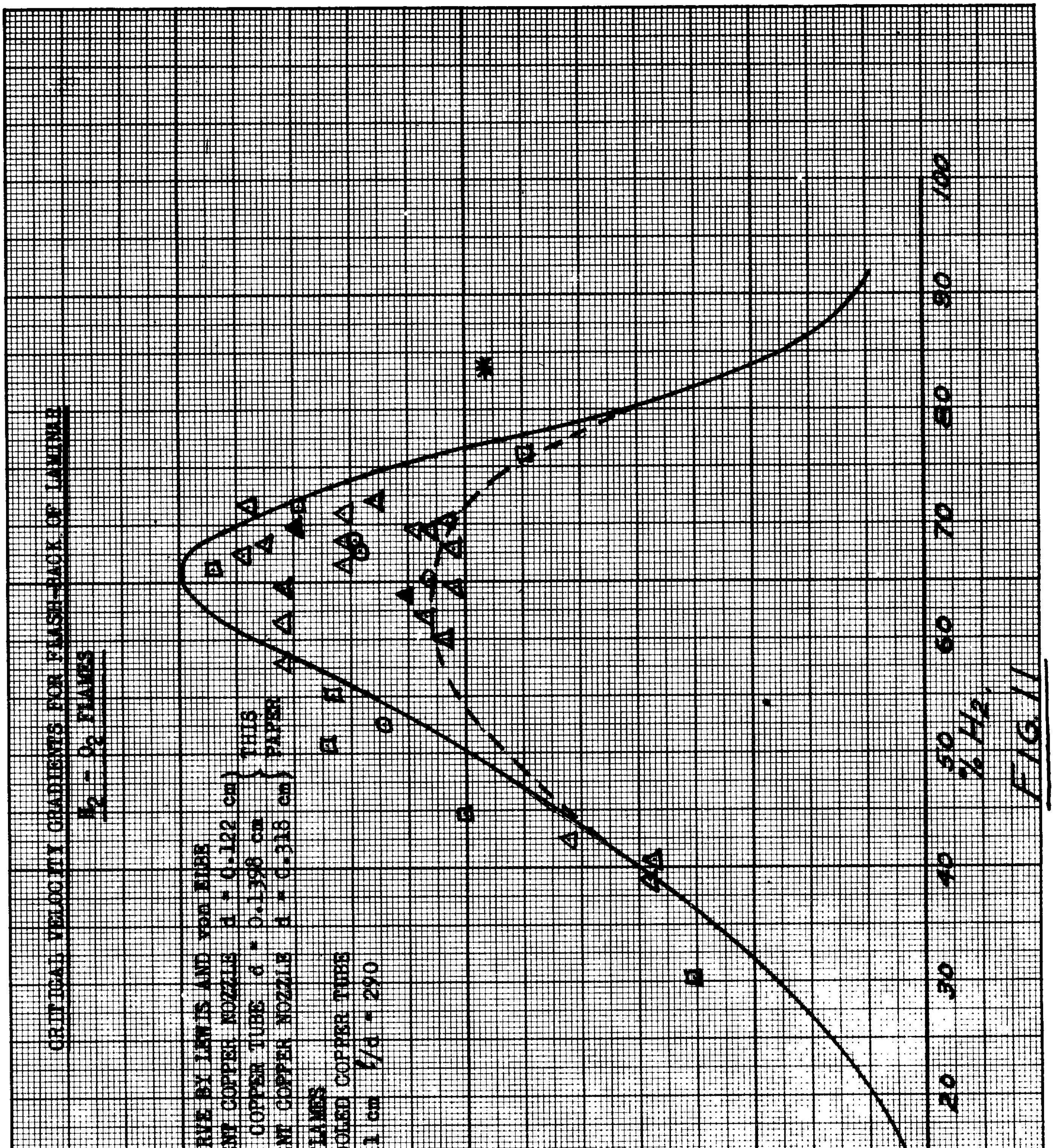


FIG. 11

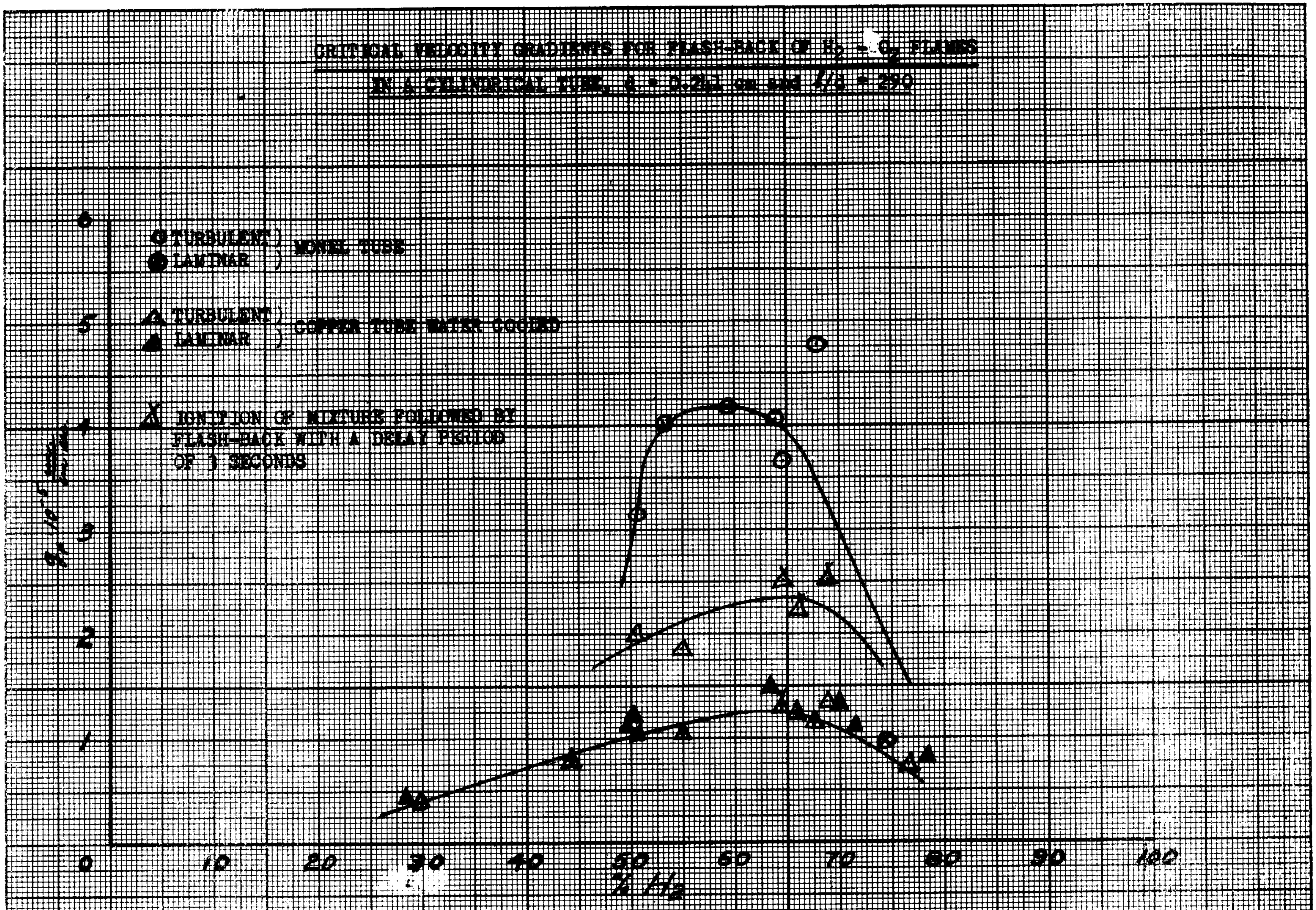

CRITICAL VELOCITY GRADIENTS FOR FLASH-BACK OF H_2 - O_2 FLAMES
IN A CYLINDRICAL TUBE
TURBULENT) LAMINAR) MONEL TUBE
TURBULENT) LAMINAR) COPPER TUBE WATER COOLED
IGNITION OF MIXTURE FOLLOWED BY FLASH-BACK WITH A DELAY PERIOD OF 3 SECONDS
0
1
2
3
4
5
6
10
20
30
40
50
60
70
80
90
100
% H_2

FIG 12

NO. 340 M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

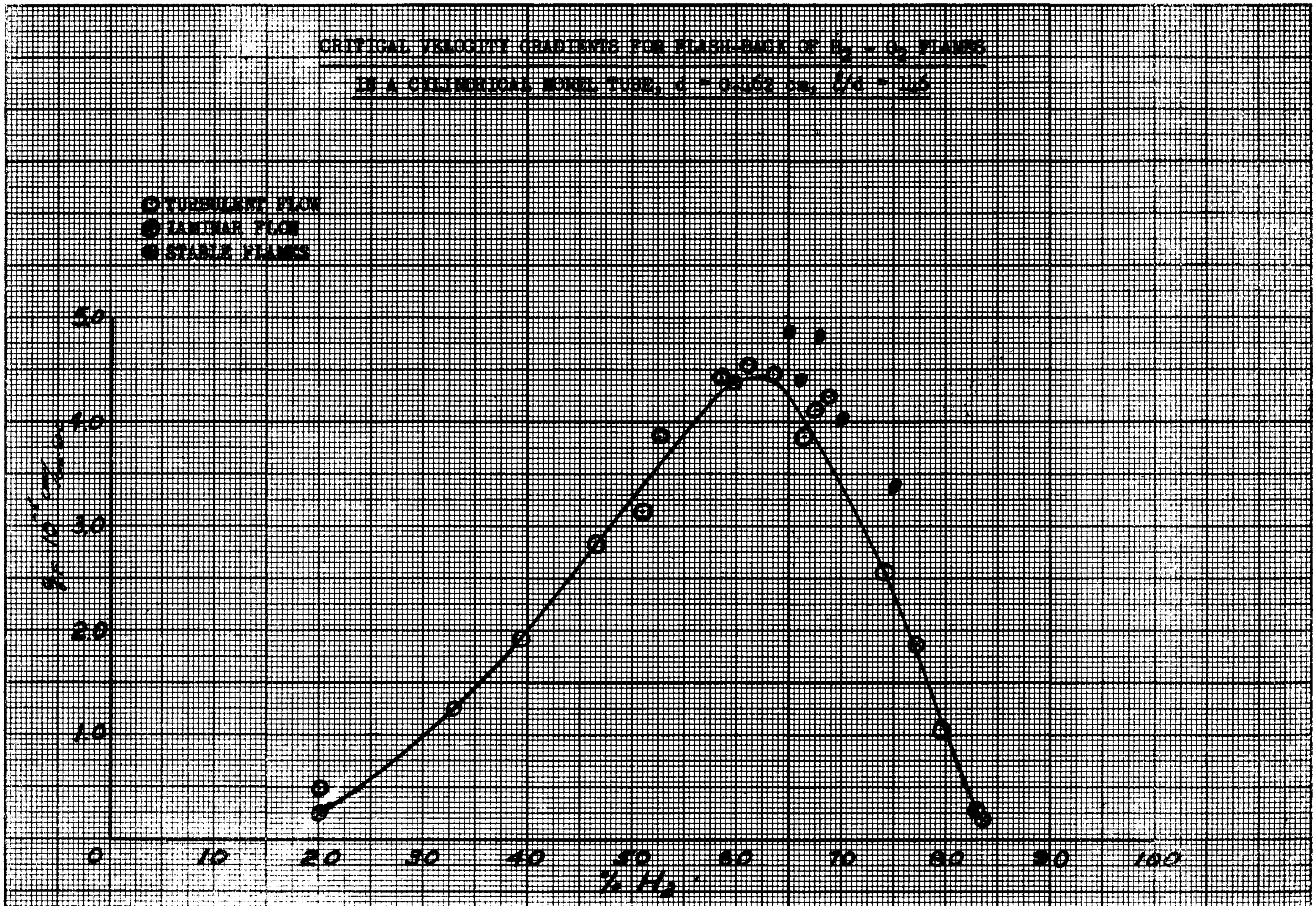
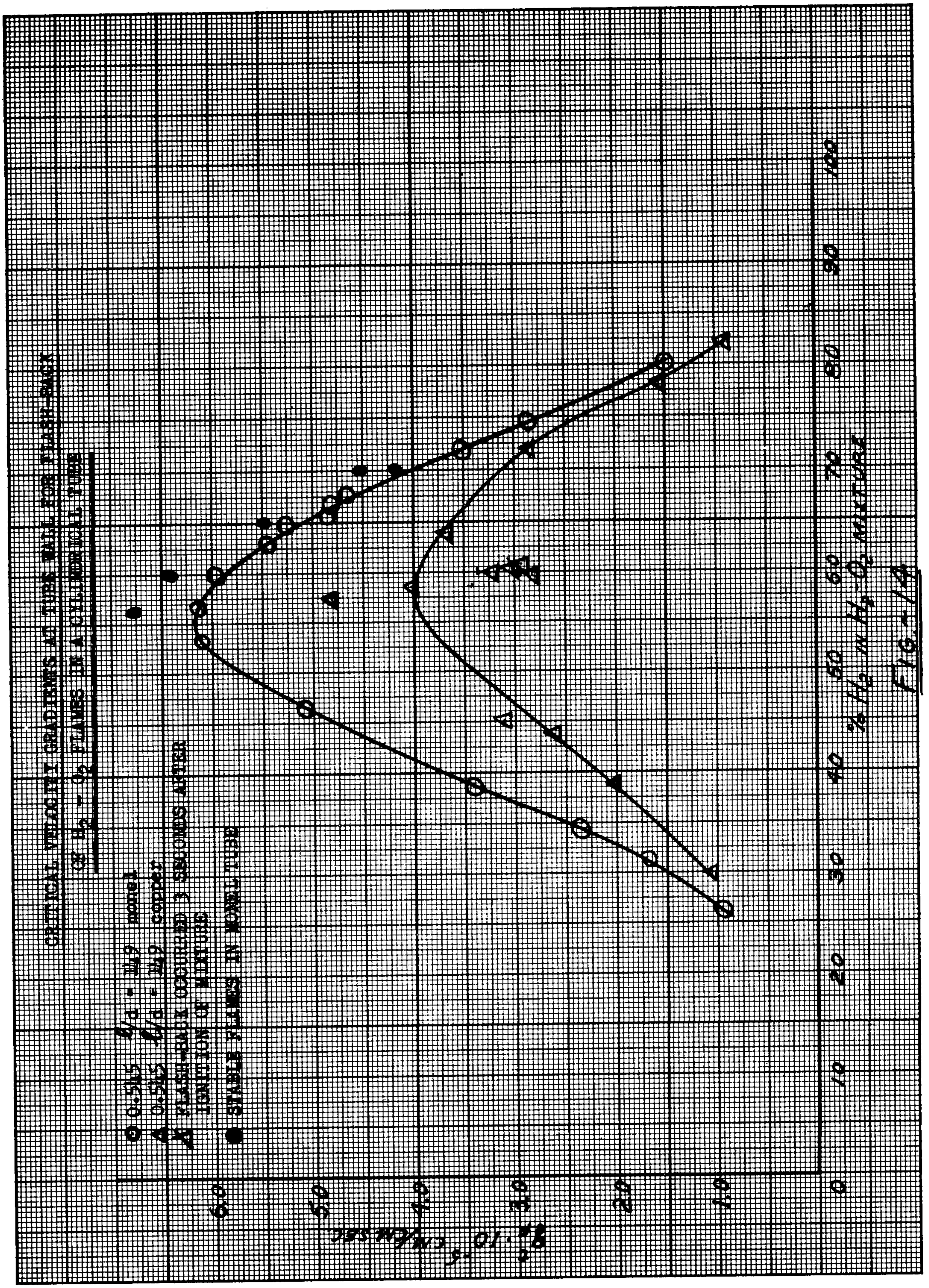


FIG. 13


CRITICAL VELOCITY GRADIENTS AT TUBE WALL FOR FLASH-BACK
OF H_2 - O_2 FLAMES IN A CYLINDRICAL TUBE
0.515 ℓ/d - 14.9 monel
0.515 ℓ/d - 14.9 copper
FLASH-BACK OCCURRED 3 SECONDS AFTER IGNITION OF MIXTURE
STABLE FLAMES IN MONEL TUBE
$g_F \cdot 10^{-5}$, cm/cm sec
1.0
2.0
3.0
4.0
5.0
6.0
0
10
20
30
40
50
60
70
80
90
100
% H_2 in H_2-O_2 MIXTURE
FIG-14

NO. 340- M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

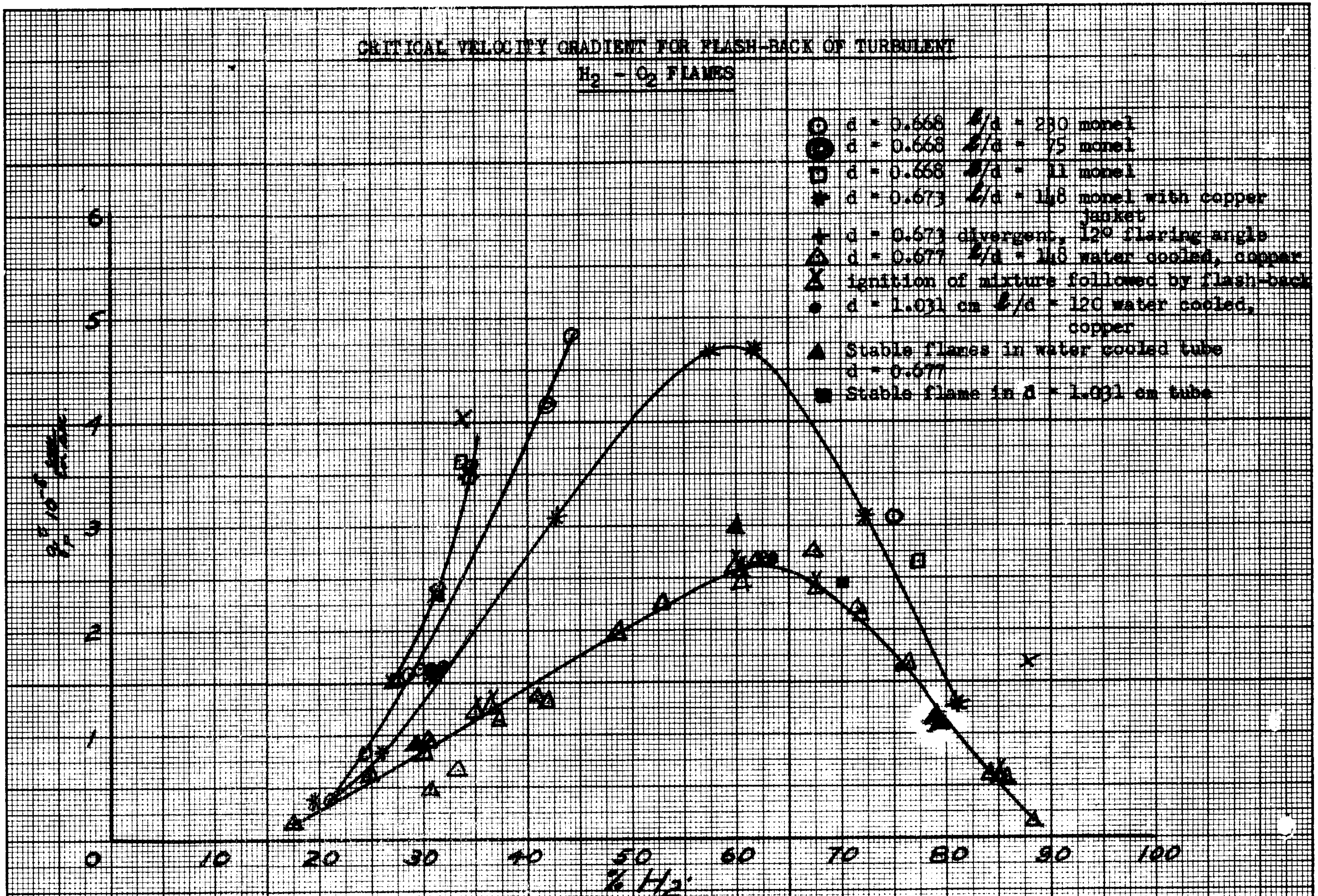
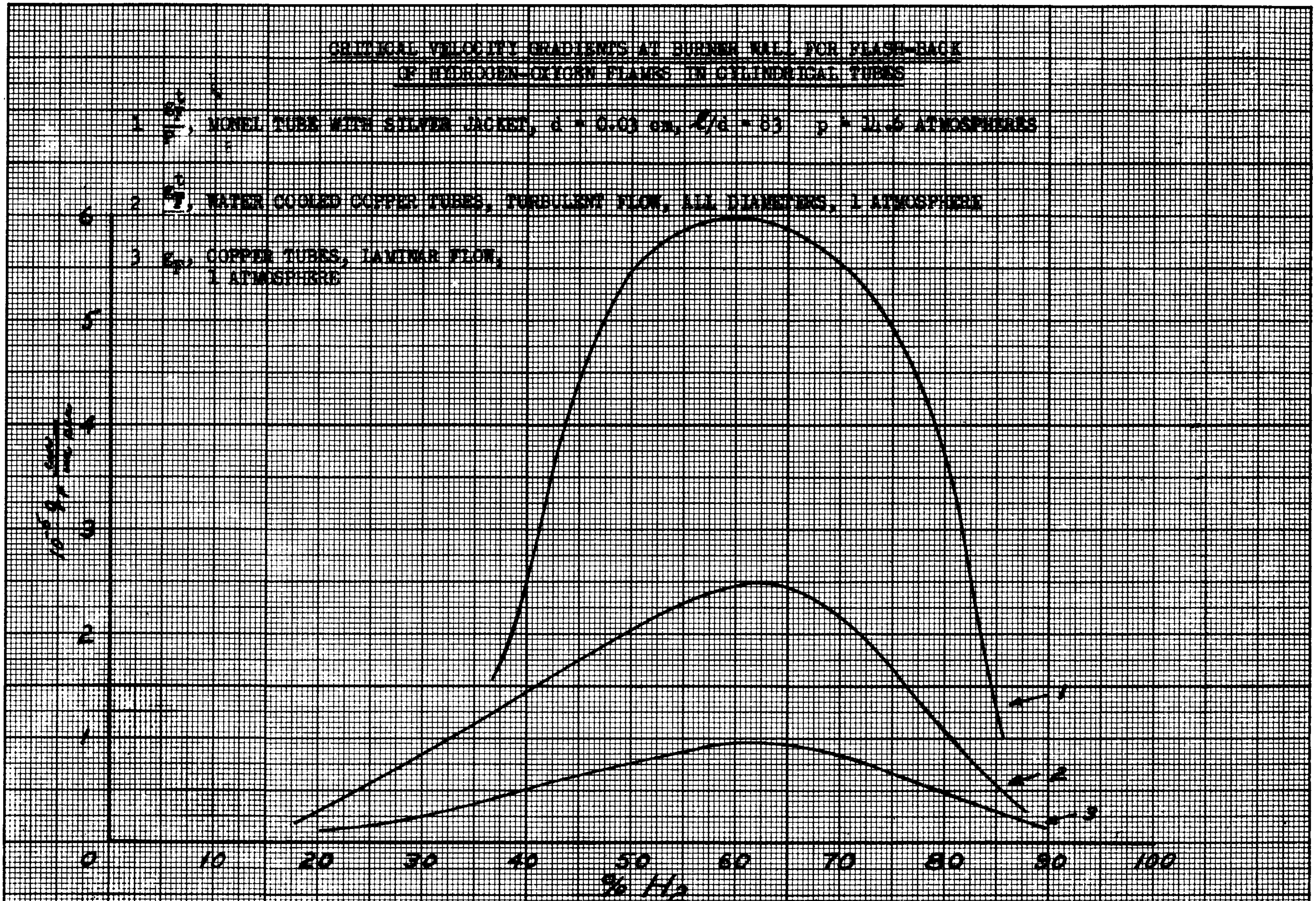


FIG 15



CRITICAL VELOCITY GRADIENTS AT BURNER WALL FOR FLASH-BACK
OF HYDROGEN-OXYGEN FLAMES IN CYLINDRICAL TUBES
1 g_F^t, MONEL TUBE WITH SILVER JACKET, d = 0.03 cm, ℓ/d = 83 p = 11.6 ATMOSPHERES
2 g_F^t, WATER COOLED COPPER TUBES, TURBULENT FLOW, ALL DIAMETERS, 1 ATMOSPHERE
3 g_F, COPPER TUBES, LAMINAR FLOW, 1 ATMOSPHERE
0
1
2
3
4
5
6
10
20
30
40
50
60
70
80
90
100
% H_2

FIG 16

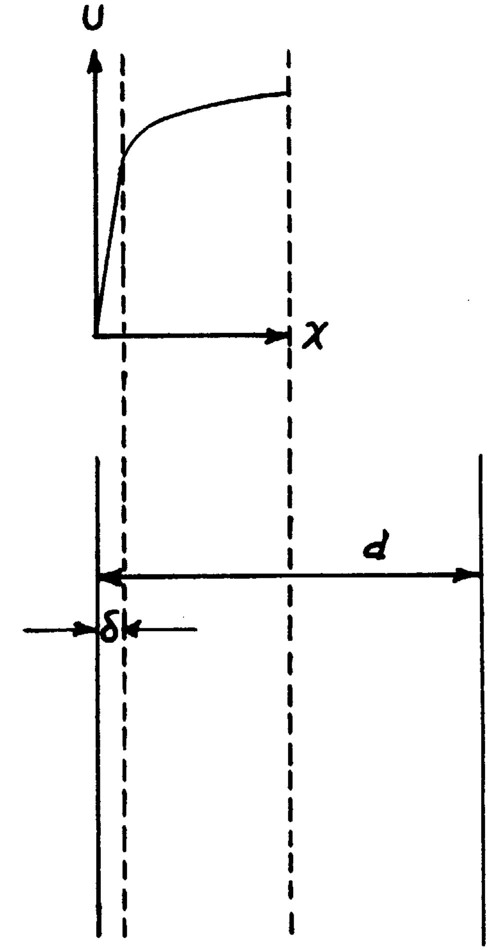


FIG.-17

VELOCITY DISTRIBUTION OF TURBULENT GAS FLOW IN A CYLINDRICAL TUBE

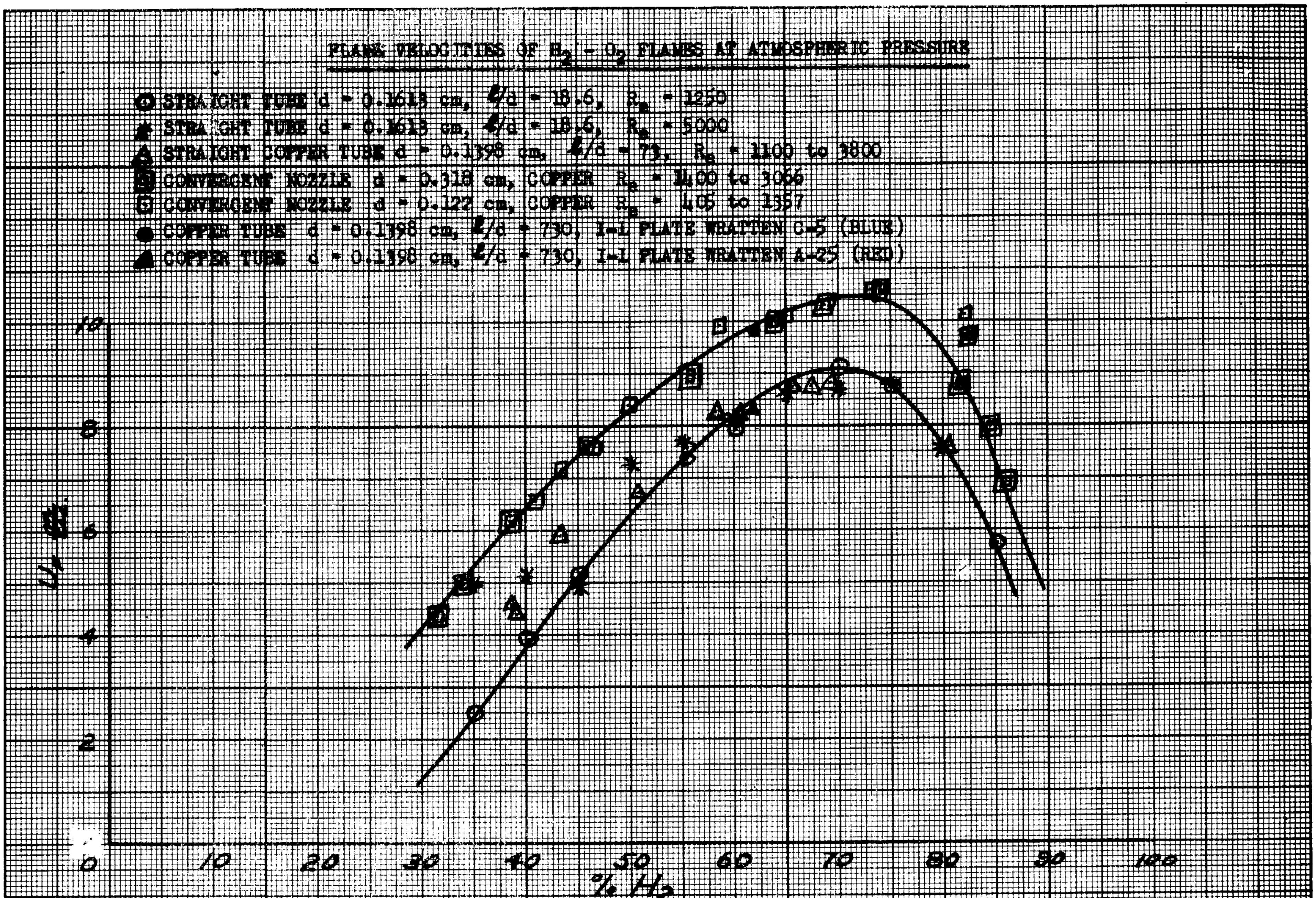

FLAME VELOCITIES OF $H_2 - O_2$ FLAMES AT ATMOSPHERIC PRESSURE
STRAIGHT TUBE d = 0.1618 cm, ℓ/d = 18.6, R_e = 1250
STRAIGHT TUBE d = 0.1618 cm, ℓ/d = 18.6, R_e = 5000
STRAIGHT COPPER TUBE d = 0.1398 cm, ℓ/d = 73, R_e = 1100 to 3800
CONVERGENT NOZZLE d = 0.318 cm, COPPER R_e = 1400 to 3066
CONVERGENT NOZZLE d = 0.122 cm, COPPER R_e = 405 to 1357
COPPER TUBE d = 0.1398 cm, ℓ/d = 730, I-L PLATE WRATTEN C-5 (BLUE)
COPPER TUBE d = 0.1398 cm, ℓ/d = 730, I-L PLATE WRATTEN A-25 (RED)
0
2
4
6
8
10
10
20
30
40
50
60
70
80
90
100
% H_2

FIG 18

NO. 340-M DIETZGEN GRAPH PAPER
MILLIMETER
EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

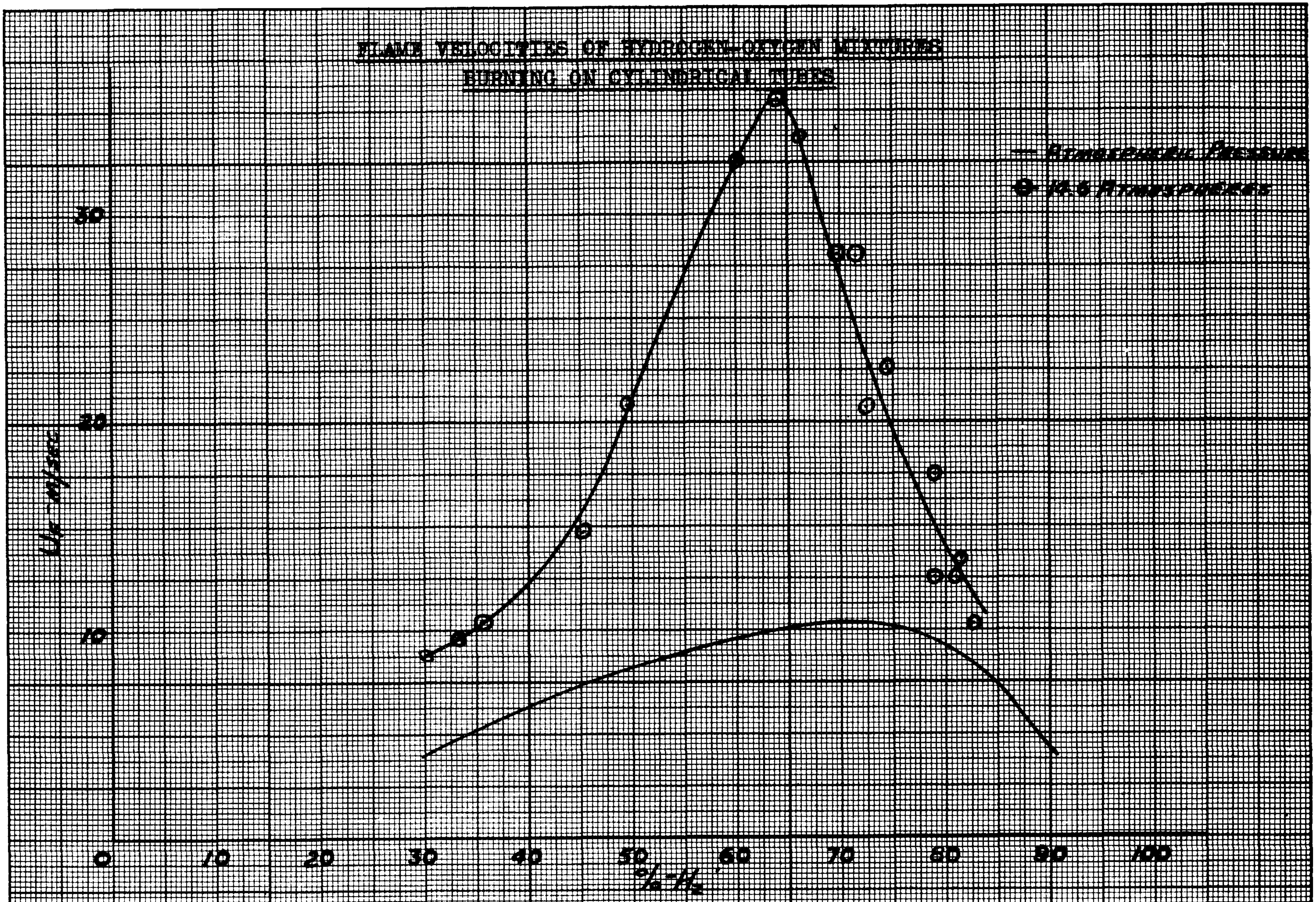


FIG-19

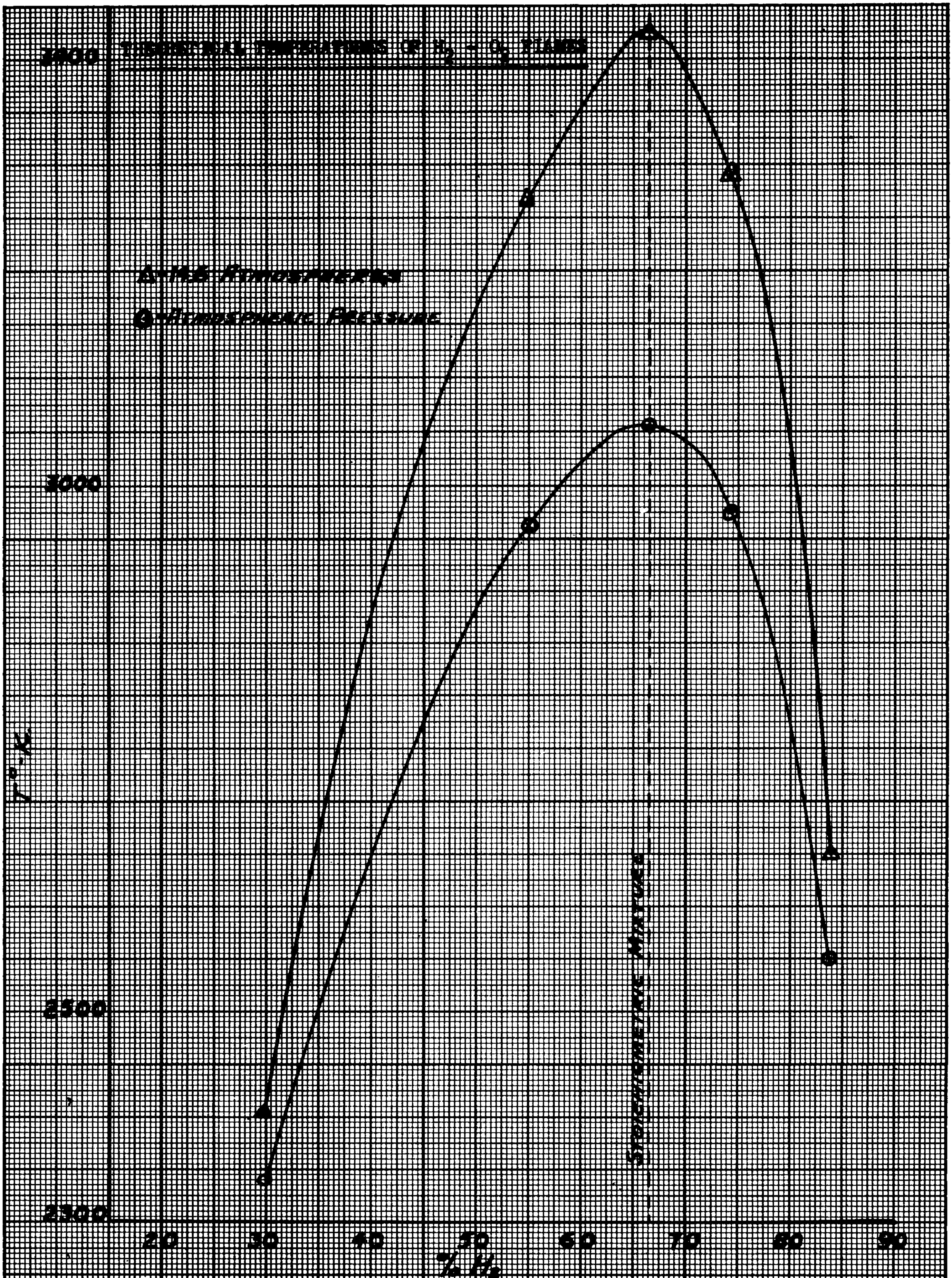

ATMOSPHERIC PRESSURE
3000
2500
2300
T °K
STOICHIOMETRIC MIXTURE
20
30
40
50
60
70
80
90
% H_2

Fig-20

NO. 340· M DIETZGEN GRAPH PAPER
MILLIMETER

EUGENE DIETZGEN CO.
PRINTED IN U. S. A.

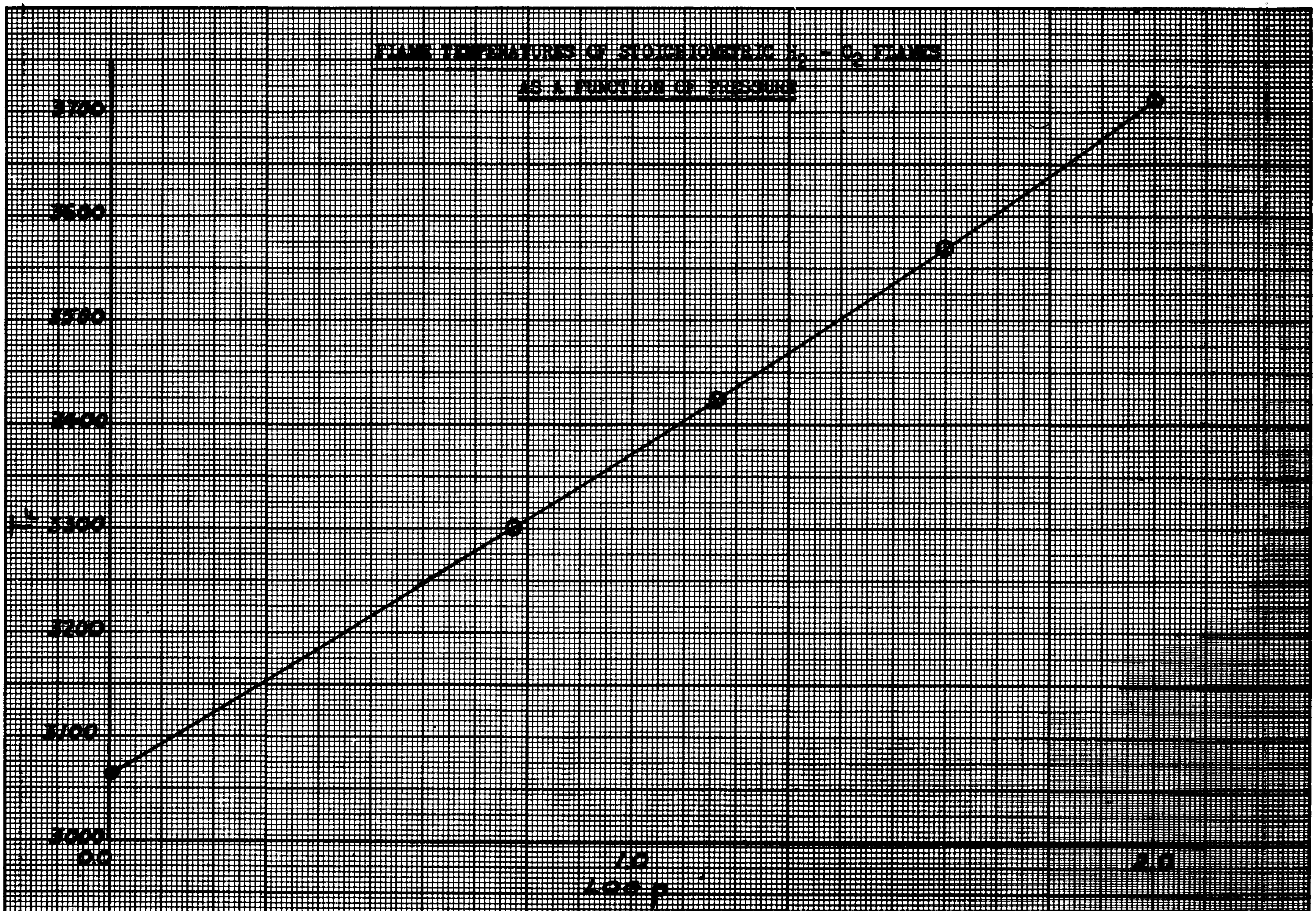


FIG.-21

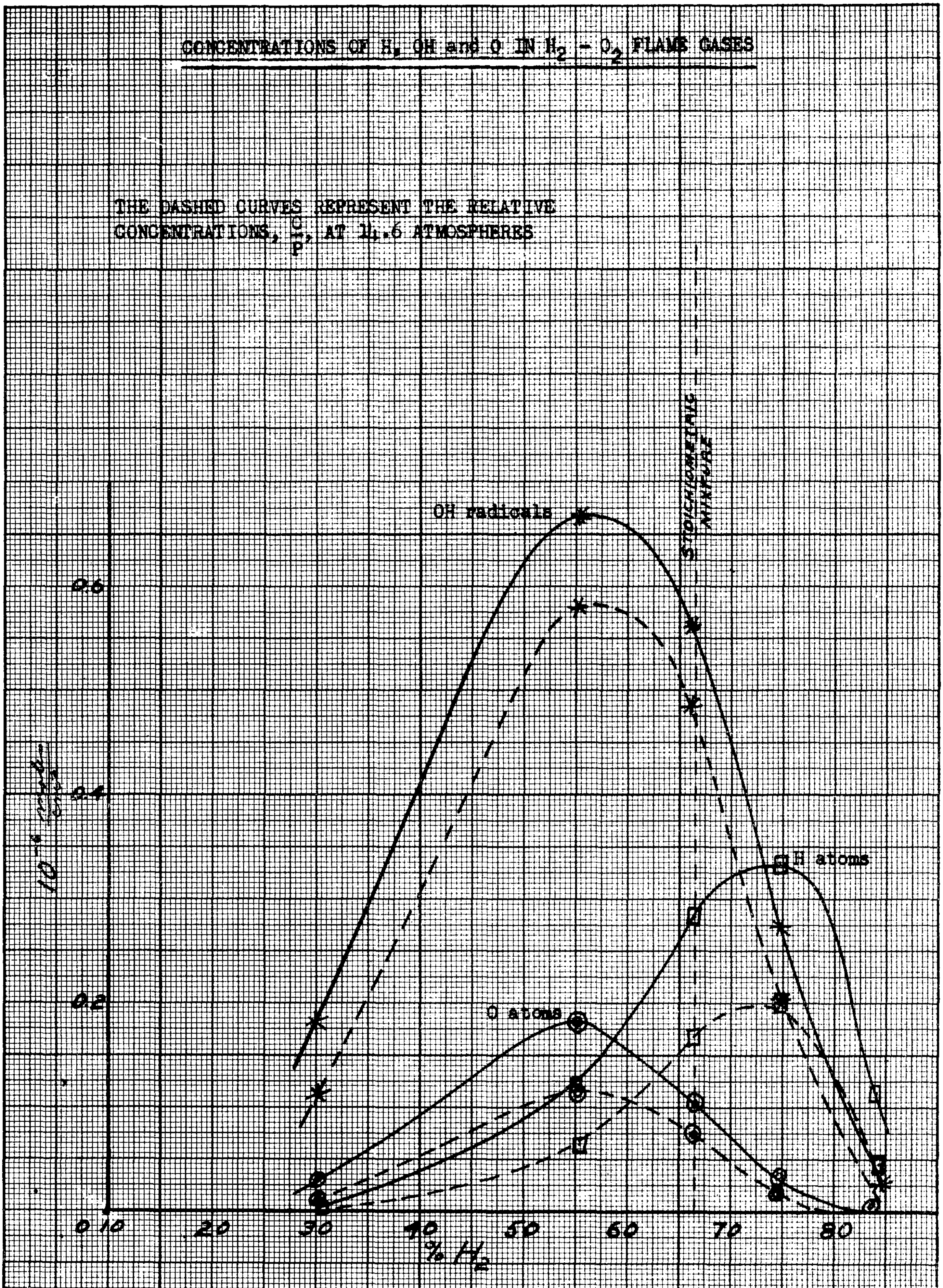

CONCENTRATIONS OF H, OH and O IN H_2 - O_2 FLAME GASES
THE DASHED CURVES REPRESENT THE RELATIVE CONCENTRATIONS, $\frac{C}{P}$, AT 14.6 ATMOSPHERES
OH radicals
H atoms
O atoms
STOICHIOMETRIC MIXTURE
0.6
0.4
0.2
0
10
20
30
40
50
60
70
80
% H_2

FIG 22

MILLIMETER PRINTED IN U. S. A.

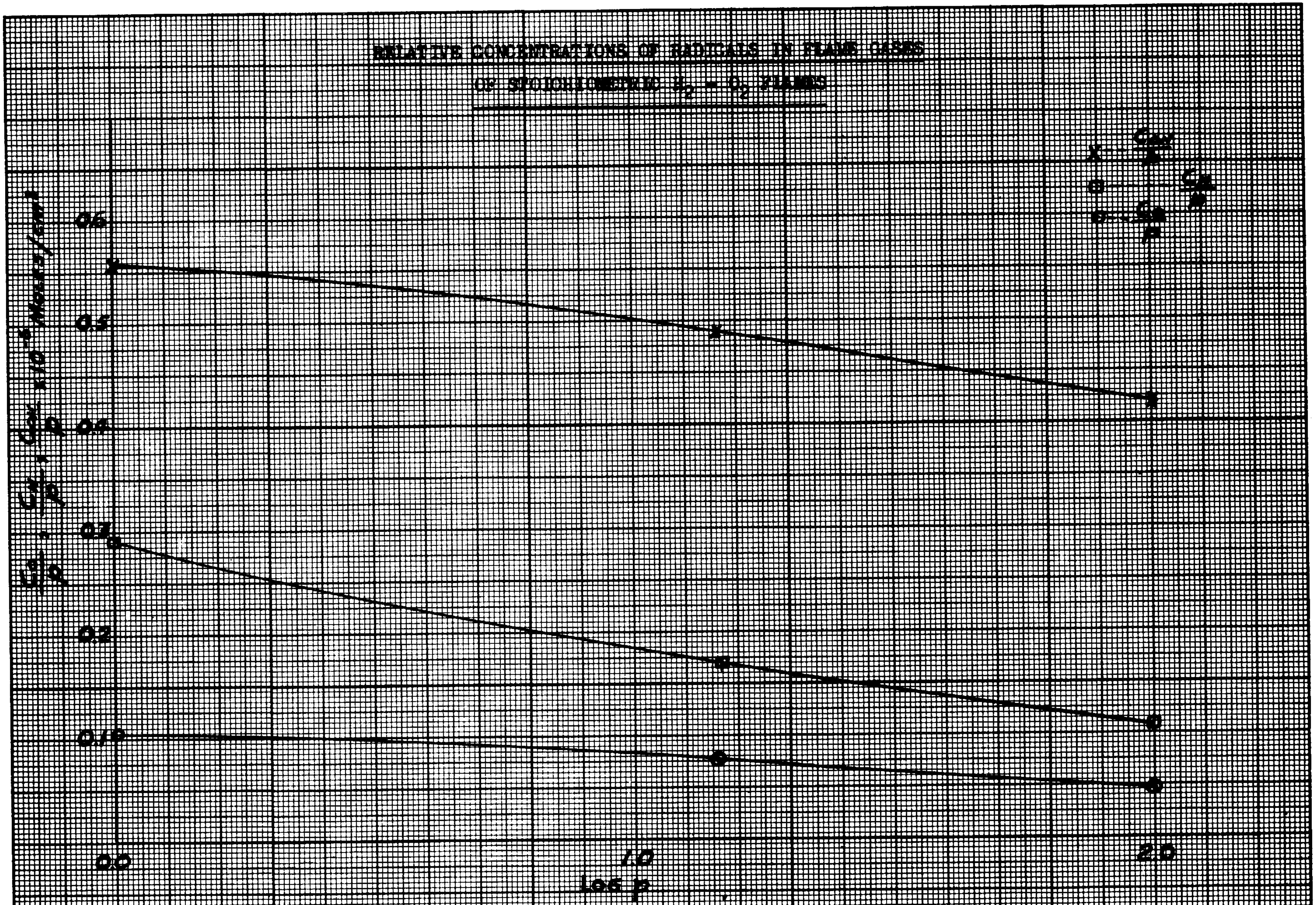


FIG-23

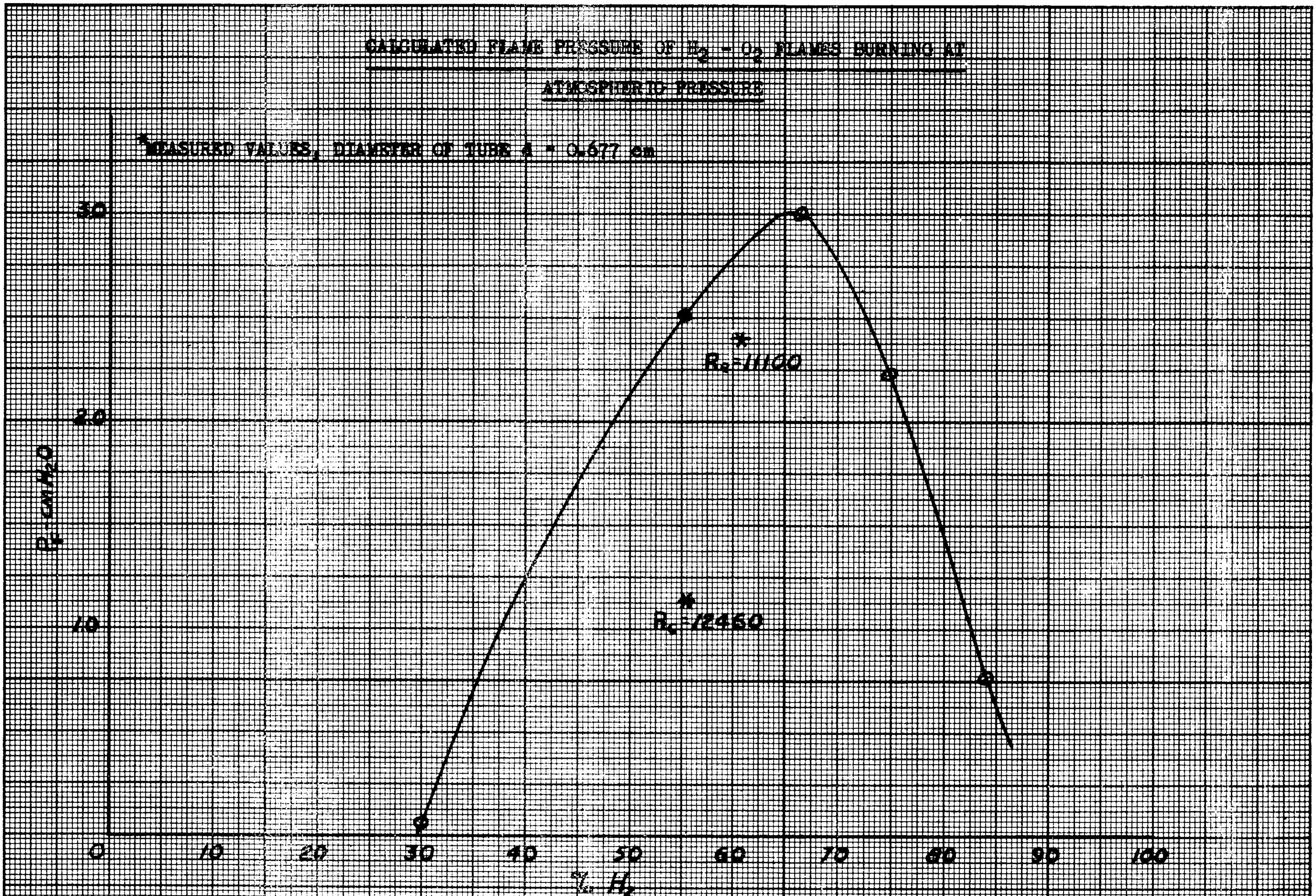

CALCULATED FLAME PRESSURE OF H_2 - O_2 FLAMES BURNING AT
ATMOSPHERIC PRESSURE
*MEASURED VALUES, DIAMETER OF TUBE A = 0.677 cm
30
20
10
P - cm H_2O
* R_e=1100
* R_e=12460
0
10
20
30
40
50
60
70
80
90
100
% H_2

FIG - 24

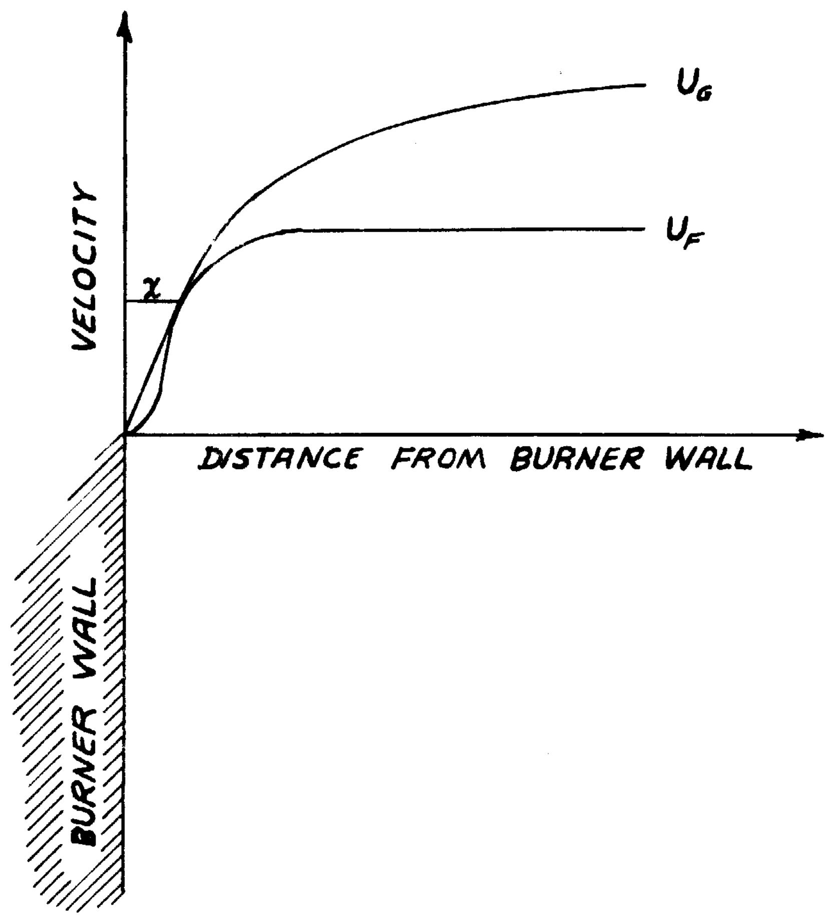


FIG.~25

CONDITIONS FOR FLASH-BACK OF BURNER FLAMES

FIG. 26
d = 0.462 cm
49.5 % H_2
v_o = 787 cm^3/sec
$\overline{U}_G$ = 46.9 m/sec
R_e = 8270
$g^t = 3.45 \times 10^5 \frac{cm}{sec\ cm}$

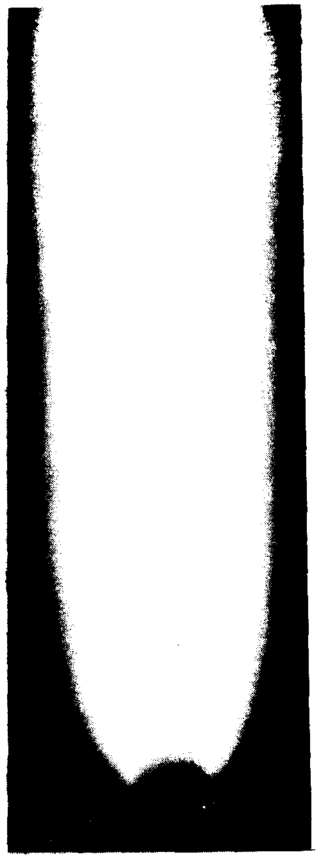


FIG. 27
d = 0.241 cm(water cooled)
71.5 % H_2
v_o = 150 cm^3/sec
$\overline{U}_G$ = 33.0 m/sec
R_e = 2155

FIG. 28
d = 0.1303 cm, convergent
64.1 % H_2
v_o = 24.3 cm^3/sec
$\overline{U}_G$ = 18.2 m/sec
R_e = 726

FIG. 29
d = 0.462 cm
27.8 % H_2
v_o = 464 cm^3/sec
$\overline{U}_G$ = 27.7 m/sec
R_e = 6358

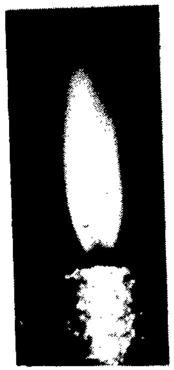


FIG. 30
p = 14.6 atm
d = 0.03 cm
59.9 % H_2
v_o = 90.1 cm^3/sec
$\overline{U}_G$ = 87.2 m/sec
R_e = 12460

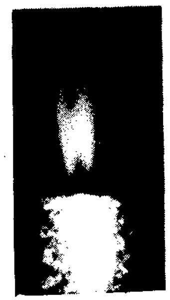


FIG. 31
p = 14.6 atm
d = 0.03 cm
45.5 % H_2
v_o = 72.5 cm^3/sec
$\overline{U}_G$ = 70.2 m/sec
R_e = 11900

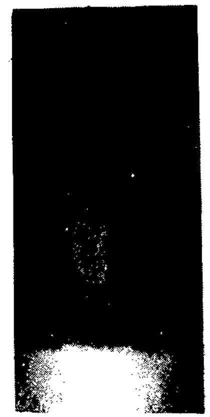


FIG. 32
p = 14.6 atm
d = 0.03 cm
74.5 % H_2
v_o = 160.9 cm^3/sec
$\overline{U}_G$ = 155.5 m/sec
R_e = 17570

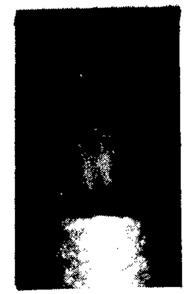


FIG. 33
p = 14.6 atm
d = 0.03 cm
49.6 % H_2
v_o = 78.5 cm^3/sec
$\overline{U}_G$ = 76.0 m/sec
R_e = 12700

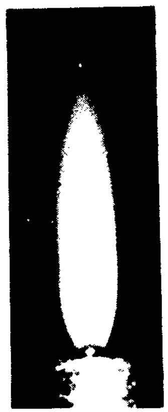


FIG. 34
p = 14.6 atm
d = 0.03 cm
66.4 % H_2
v_o = 77.4 cm^3/sec
$\overline{U}_G$ = 74.9 m/sec
R_e = 9650

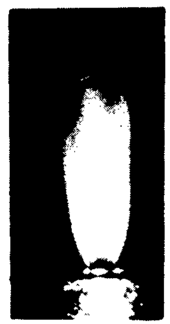


FIG. 35
p = 14.6 atm
d = 0.03 cm
69.9 % H_2
v_o = 75.5 cm^3/sec
$\overline{U}_G$ = 73.1 m/sec
R_e = 8940

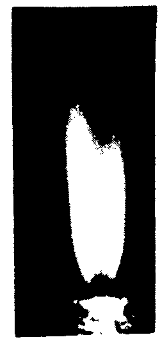


FIG. 36
p = 14.6 atm
d = 0.03 cm
72.6 % H_2
v_o = 70.1 cm^3/sec
$\overline{U}_G$ = 67.9 m/sec
R_e = 7970

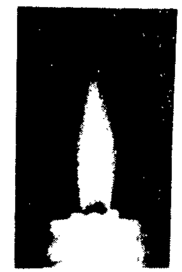


FIG. 37
p = 14.6 atm
d = 0.03 cm
81.0 % H_2
v_o = 35.5 cm^3/sec
$\overline{U}_G$ = 34.5
R_e = 3380

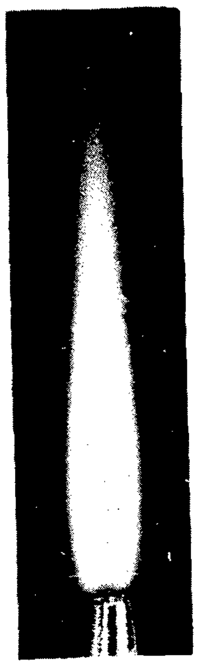


FIG. 38
p = 1 atm
d = 0.03 cm
55.6 % H_2
$\underline{v}_o$ = 9.7 cm^3/sec
$\overline{U}_G$=137.5 m/sec
R_e=1438

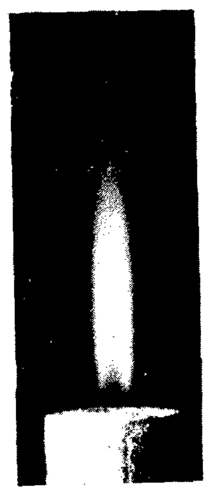


FIG. 39
p = 1 atm
d = 0.03 cm
41.6 % H_2
$\underline{v}_o$ = 8.1 cm^3/sec
$\overline{U}_G$=114.9 m/sec
R_e=1449

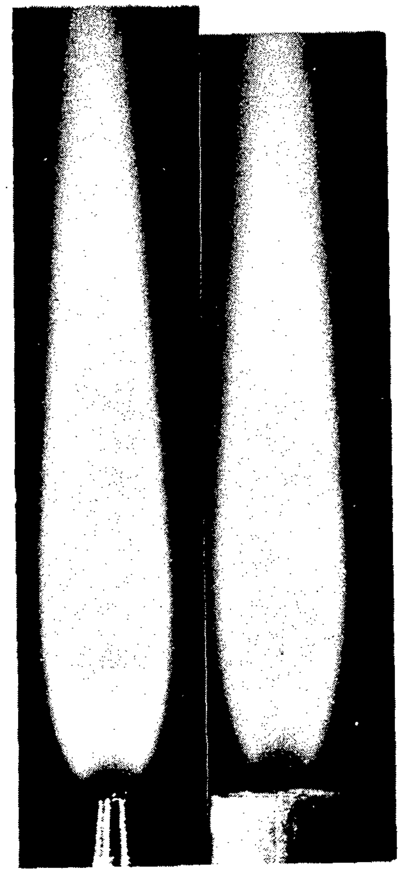


FIG. 40
p = 1 atm
d = 0.03 cm
75.0 % H_2
$\underline{v}_o$ = 12.0 cm^3/sec
$\overline{U}_G$=170.0 m/sec
R_e=1309

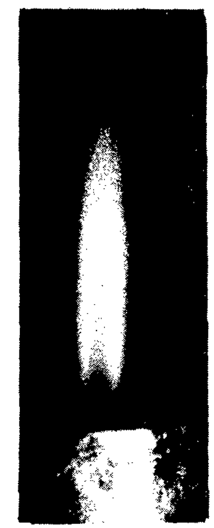


FIG. 41
p = 1 atm
d = 0.03 cm
47.4 % H_2
$\underline{v}_o$ = 8.7 cm^3/sec
$\overline{U}_G$=123.9 m/sec
R_e=1430

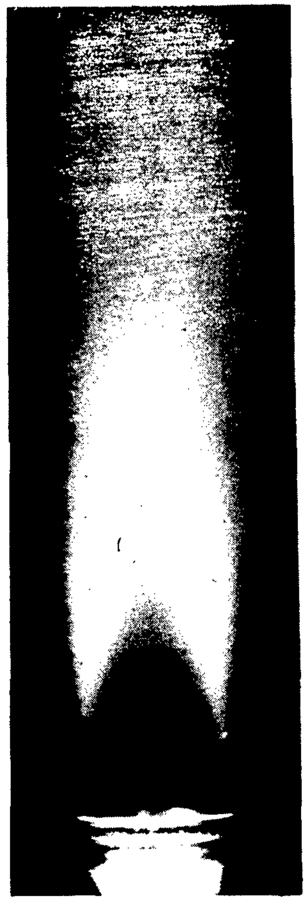


FIG. 42
d = 0.462 cm
40.6 % H_2
v_o = 1076 cm^3/sec
$\overline{U}_G$ = 64 m/sec
R_e = 12710
U_F = 6 m/sec

TABLE I

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

BURNER	d	$\frac{\ell}{d}$	$\%H_2$	p_c	v_o	$\overline{U}_G$	R_e	$10^{-5}\frac{g_F^t}{p_c}$	$10^{-5}g_F$	$10^{-5}\frac{g_F}{p_c}$	$10^{-5}g_{F\,ref.5}$
COPPER	0.1398	73	39.7	1.6	85.1	34.5	3370	2.65			0.5
			71.1	2.6	6.3	26.2	645		6.1	2.4	1.15
			68.0	3.0	8.8	31.3	935		7.3	2.4	1.27
			64.6	4.0	23.5	63.6	2650	6.7			1.29
COPPER	0.0343	47	69.0	4.1	19.5	52.0	2066		12.1	3.0	1.23
			65.0	4.5	44.6	106.1	5010	15.8			1.30
			63.5	4.7	35.4	80.5	4060	9.8			1.28
			65.0	7.4	53.2	77.9	5990	8.2			1.30
			68.4	15.0	162.5	117.3	17310	14.1			1.25
			65.6	6.8	22.8	46.0	2824	3.4			1.30
			65.6	7.0	22.8	44.6	2824	3.2			1.30
STAINLESS	0.0305	295	65.6	8.1	22.8	38.6	2824	2.4			1.30
STEEL			65.6	11.9	22.8	26.3	2824	1.1			1.30
			64.1	11.9	61.0	70.1	7750	6.3			1.28
			69.1	20.3	217.2	146.3	25750	18.8			1.23
			40.0	8.9	60.0	95.4	11060	15.1			0.51
			40.0	9.5	60.0	89.4	11060	13.3			0.51
MONEL	0.0300	870	40.0	14.0	112.5	123.7	20770	21.7			0.51
			66.7	13.4	180.0	190.0	22360	33.9			1.29
			77.0	70.2	56.5	11.5	5880	0.15			0.75
			83.7	71.0	113.9	22.7	10060	0.42			0.32

TABLE II

FLASH-BACK CONDITIONS OF H_2-AIR FLAMES

BURNER	d	ℓ/d	$\%H_2$	p_c	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F t \frac{1}{p_c}$	$10^{-5} g_F$	$10^{-5} \frac{g_F}{p_c}$	$10^{-5} g_{F_{ref.5}}$
			23.1	1.0	2.6	1.7	113		0.0972	0.0972	0.050
			31.5	3.9	47.7	8.0	2070		0.4580	0.1175	0.093
			33.4	5.0	91.6	12.0	3980	0.335			0.100
COPPER	0.1398	730	30.7	5.5	97.7	11.6	4240	0.314			0.091
			33.4	12.4	238.8	12.5	10370	0.287			0.100
			33.4	13.3	238.8	11.7	10370	0.251			0.100
			33.3	19.4	18.0	13.1	3640	0.409			0.100
MONEL	0.030		36.0	40.4	25.0	8.8	5050	0.164			0.108
			38.3	69.1	19.6	4.0	3660	0.036			0.111

TABLE III

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT 14.6 ATMOSPHERES

MONEL TUBE, d=0.03cm $\frac{\ell}{d}$=870

$\%H_2$	$\bar{U}_G$	R_e	$10^{-5}\frac{g_F^t}{p_c}$
54.1	93.6	14690	11.1
60.9	97.7	13850	11.1
67.5	151.5	19290	22.1
68.6	76.8	9610	6.7
69.7	109.8	13590	12.5
70.8	87.2	10620	8.1
71.9	88.5	10560	8.2
72.1	86.9	10300	7.9
73.8	107.7	12430	11.3
74.1	194.1	22270	31.5
74.4	135.9	15500	16.8
75.6	91.5	10200	8.3
75.8	201.3	22400	32.9
76.0	60.6	6700	4.0
76.1	75.9	8350	5.9
76.4	129.0	14130	15.0
76.4	114.7	12640	12.2
76.8	108.8	11890	11.1
77.1	97.3	10490	9.0
77.1	131.7	14210	15.3
77.2	67.5	7260	4.7
77.3	132.7	14275	15.4
77.4	67.8	7310	4.8
77.5	81.9	8740	6.6
77.7	101.6	10800	9.7
77.8	74.3	7910	5.6
77.9	110.9	11740	10.2
78.1	81.0	8520	6.4
78.8	58.5	6080	3.6
78.8	63.4	6600	4.1
78.9	71.2	7370	5.1
79.2	58.7	6020	3.6
79.5	68.9	7040	4.7
80.0	57.7	5820	3.9
80.1	65.1	6540	4.2
80.1	58.3	5850	3.5
81.0	69.3	6840	4.7
81.0	57.0	5620	3.3
82.0	58.1	5570	3.4
82.5	60.8	5790	3.6
83.0	51.6	4830	2.8
90.5	50.5	3720	2.1

TABLE IV

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT 14.6 ATMOSPHERES

MONEL TUBE, d=0.0693cm $\frac{\ell}{d}$= 382

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}\frac{g_F^t}{p_c}$
83.5	407.1	73.5	15700	3.97
83.9	372.3	67.3	14230	3.37
85.0	329.0	59.4	12140	2.64

TABLE V

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT 14.6 ATMOSPHERES

MONEL TUBE WITH SILVER JACKET, d=0.03cm $\frac{\ell}{d}$= 83

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}\frac{g_F^t}{p_c}$
37.8	28.55	27.85	5450	1.58
42.8	51.70	50.00	9130	4.18
46.4	105.8	101.8	17880	14.0
50.4	65.4	62.9	10390	5.7
55.9	89.4	86.0	13060	9.4
58.6	110.8	106.7	15030	13.4
59.1	68.5	65.9	9620	5.7
66.1	56.6	54.6	7060	3.8
66.4	77.4	74.9	9650	6.5
69.9	63.5	61.5	7500	4.4
70.4	71.8	69.0	8440	5.4
71.6	80.6	77.5	9240	6.5
74.0	40.5	40.6	4500	2.1
79.0	64.4	61.9	6390	4.0
85.4	31.3	30.2	2630	1.0

TABLE VI

FLASH-BACK CONDITIONS OF LAMINAR

H_2-O_2 FLAMES AT ATMOSPHERIC PRESSURE

BURNER	d	$\frac{l}{d}$	$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F$	$10^{-5} g_{F\,ref.5}$
			52.8	16.73	14.3	632	0.94	0.89
CONVERGENT			65.1	15.36	13.1	480	0.86	1.30
COPPER	0.122		67.6	17.45	14.9	525	0.98	1.28
NOZZLE			68.5	16.50	14.1	492	0.93	1.25
			68.6	16.60	14.2	494	0.93	1.25
			42.5	16.5	10.8	395	0.62	0.58
STRAIGHT			68.0	21.6	14.1	565	0.81	1.27
COPPER	0.1398	73	68.0	21.6	14.1	565	0.81	1.27
TUBE			69.5	22.4	15.6	601	0.89	1.22
			69.5	21.5	15.0	572	0.86	1.22
			38.8	12.9	8.4	512	0.48	0.47
			40.5	12.6	8.2	494	0.47	0.52
			58.0	30.0	19.6	916	1.12	1.10
			59.9	22.0	14.4	654	0.82	1.18
			61.6	30.0	19.6	870	1.12	1.23
			62.0	23.2	15.2	668	0.87	1.24
			64.6	22.0	14.4	608	0.82	1.29
STRAIGHT			64.6	30.0	19.6	828	1.12	1.29
COPPER	0.1398	730	66.4	28.6	18.7	769	1.07	1.30
TUBE			67.6	31.6	20.7	831	1.19	1.28
			68.3	30.7	20.1	803	1.15	1.26
			68.4	30.7	20.1	802	1.15	1.26
			68.5	27.9	18.2	724	1.04	1.25
			70.2	22.2	14.5	566	0.83	1.19
			71.0	27.4	17.9	689	1.03	1.15
			71.8	31.3	20.5	778	1.18	1.11
			72.0	25.7	16.8	635	0.96	1.10
CONVERGENT COPPER NOZZLE	0.318		83.4	107.5	13.4	891	0.77	0.34

TABLE VII

FLASH BACK CONDITIONS OF H_2-O_2 FLAMES AT ATMOSPHERIC PRESSURE

MONEL TUBE, d=0.241cm $\frac{\ell}{d}$= 290

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$	$10^{-5}g_F$
50.6	186	40.8	3670	3.13	
53.2	218	47.8	4190	4.01	
59.1	231.8	50.8	4040	4.19	
63.9	235	51.6	3800	4.06	
64.5	222.6	48.8	3564	3.67	
67.9	265.4	58.2	4019	4.77	
74.5	129	28.3	1768		0.94

WATER COOLED COPPER TUBE d=0.241cm $\frac{\ell}{d}$= 290

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$	$10^{-5}g_F$
29.75	55.2	12.1	1430		0.40
44.25	110.2	24.2	2440		0.80
50.60	142.4	31.2	2810	2.00	1.04
55.05	142.0	31.2	2656	1.87	1.03
64.7	178.4	39.2	2850	2.48	1.3
66.1	170.2	37.4	2658	2.24	1.24
67.6	159.9	35.1	2440		1.17
68.9	184.4	40.5	2776	2.52	1.35
75.9	95.0	20.9	1266		0.69
76.9	105.2	23.1	1378		0.77

TABLE VIII

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT ATMOSPHERIC PRESSURE

MONEL TUBE, d=0.462cm $\frac{l}{d}$= 146

%H_2	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$	$10^{-5}g_F$
20.9	210	12.5	3070	0.44	
32.8	393	23.4	5120	1.21	
39.5	529	31.5	6315	1.90	
46.4	685	40.8	7525	2.80	
51.0	755	44.9	7710	3.14	
52.8	850	50.6	8500	3.82	
58.4	959	57.1	8790	4.40	
59.6	962	57.3	8700	4.36	
61.0	988	58.9	8750	4.52	
63.4	996	59.4	8460	4.45	
65.8	982	58.5	8020	4.22	
66.4	932	55.6	7550	3.83	
67.5	979	58.4	7790	4.10	
68.8	1000	59.6	7810	4.21	
74.1	777	46.2	5580	2.55	
77.3	663	39.5	4475	1.83	
79.6	482	28.7	3080	1.01	
83.0	252	15.0	1474		0.26
83.6	154	9.2	884		0.16

TABLE IX

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT ATMOSPHERIC PRESSURE

MONEL TUBE, d=0.545 $\frac{l}{d}$= 149

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$
26.32	475	20.4	5620	0.95
31.21	675	29.0	7550	1.69
34.44	838	36.0	9100	2.34
38.54	1050	45.1	10780	3.41
46.20	1372	58.9	12790	5.09
53.10	1590	68.3	13380	6.11
56.50	1630	70.0	13100	6.15
59.80	1635	70.1	12520	5.98
62.90	1588	68.1	11550	5.46
64.90	1575	67.6	11120	5.28
65.70	1517	65.0	10500	4.85
66.60	1518	65.1	10400	4.82
67.40	1475	63.4	10000	4.66
71.90	1309	56.1	8290	3.50
74.50	1207	51.8	7290	2.84
80.00	861	37.0	4630	1.49

COPPER TUBE, d=0.545cm $\frac{l}{d}$= 148

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$
38.75	775	33.3	7910	2.02
30.03	506.2	21.7	5710	1.03
43.9	932.6	40.0	9010	2.66
45.1	1031	44.3	9690	3.12
57.3	1423	61.1	11370	4.83
58.5	1290	55.4	10080	4.01
59.6	1060	45.5	8130	2.8
59.7	1155	49.6	8820	3.24
59.9	1087	46.6	8260	2.91
60.0	1100	47.3	8360	2.98
63.9	1277	54.7	9180	3.69
72.3	1166	50.0	7350	2.86
79.2	874	37.5	4690	1.56
82.4	668	28.7	3380	0.92
82.6	666	28.6	3350	0.91

TABLE X

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES

AT ATMOSPHERIC PRESSURE

MONEL TUBE, d=0.668cm $\frac{\ell}{d}$= 230

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F^t$
20.9	412	11.8	4185	0.36
24.3	659	18.9	6525	0.81
28.5	982	28.2	9350	1.57
29.6	998	28.6	9400	1.60
44.1	1910	54.6	15000	4.83
75.0	1946	55.6	9530	3.07

MONEL TUBE, d=0.668cm $\frac{\ell}{d}$= 75

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F^t$
30.1	1003	28.7	9300	1.60
31.2	1021	29.3	9310	1.63
41.8	1840	52.6	14790	4.14

MONEL TUBE, d=0.668cm $\frac{\ell}{d}$= 11

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F^t$
33.6	1618	46.4	14530	3.60
34.6	1630	46.6	14300	3.58
27.4	978	27.6	9260	1.52
31.2	1286	36.2	11670	2.37
34.2	1618	45.6	14260	3.48
77.0	1816	51.1	8500	2.64

MONEL TUBE WITH COPPER JACKET d=0.673 $\frac{\ell}{d}$= 148

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5} g_F^t$
19.8	422	11.9	4340	0.37
26.0	681	19.1	6490	0.80
31.3	1020	28.6	9220	1.57
42.6	1593	44.7	12550	3.08
57.4	2213	62.0	14210	4.69
61.8	2290	64.3	13600	4.71
72.4	1924	54.0	9800	3.10
81.2	1229	34.4	5200	1.23

TABLE XI

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES AT

ATMOSPHERIC PRESSURE, WATER COOLED COPPER TUBE

d=0.677cm $\frac{\ell}{d}$=148

FLOW OF WATER: 36cm 3/sec
TEMPERATURE OF WATER: 7.3°C

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$	$10^{-5}g_F$
17.4	242	6.73	2530	0.14	
25.1	597	16.6	5670	0.63	
30.0	702	19.5	6440	0.81	
30.2	752	20.9	6900	0.91	
30.8	512	14.2	4650	0.46	
33.2	631	17.5	5600	0.66	
35.0	903	25.1	7750	1.20	
36.3	921	25.6	7840	1.24	
37.5	852	24.4	7390	1.12	
40.8	988	27.5	8010	1.35	
41.9	984	27.4	7780	1.31	
48.7	1294	36.0	9360	1.99	
52.8	1419	39.4	9700	2.23	
59.9	1620	45.0	9890	2.58	
60.0	1582	44.0	9670	2.48	
60.1	1567	43.5	9570	2.44	
62.0	1677	46.5	9900	2.67	
62.8	1688	46.9	9890	2.70	
67.4	1769	49.2	9610	2.76	
67.6	1627	45.2	8800	2.38	
67.5	1763	49.0	9550	2.75	
71.6	1604	44.6	8430	2.20	
71.9	1575	43.7	8040	2.15	
76.5	1417	39.4	6640	1.68	
79.1	1203	33.4	5300	1.20	
79.3	1198	33.2	5260	1.19	
84.2	867	24.1	3364	0.61	
85.0	860	23.9	3160	0.60	
85.8	807	22.4	2986	0.53	
88.2	441	12.3	1509		0.15

TABLE XII

FLASH-BACK CONDITIONS OF H_2-O_2 FLAMES AT ATMOSPHERIC PRESSURE

DIVERGENT MONEL TUBE d=0.673 $\frac{\ell}{d}$= 130

FLARING ANGLE 12^o

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$
27.0	973	27.4	9240	1.51
31.1	1287	36.2	11660	2.36
33.7	1767	49.8	15630	4.05
34.4	1631	46.0	14300	3.52
87.8	1595	44.9	5580	1.69

TABLE XIII

WATER COOLED COPPER TUBE

d=1.031cm $\frac{\ell}{d}$= 120

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g_F^t$
63.1	4114	49.4	15810	2.64
75.8	3408	40.9	10640	1.64

TABLE XIV

DATA OF BURNER TUBES

TUBE NO.	d	ℓ	MATERIAL	SHAPE	WALL AT TIP
1	0.318		COPPER	CONVERGENT	HEAVY
2	0.122		COPPER	CONVERGENT	HEAVY
3	0.1398	10.2	COPPER	STRAIGHT	0.004"
4	0.1398	102.0	COPPER	STRAIGHT	0.004"
5	0.1398	102.0	COPPER	STRAIGHT	HEAVY
6	0.0305	9.0	STAINLESS STEEL	STRAIGHT	TAPERED
7	0.0343	1.6	COPPER	STRAIGHT	TAPERED
8	0.464	67.4	MONEL	STRAIGHT	TAPERED
9	0.03	26.0	MONEL	STRAIGHT	TAPERED
10	0.0693	26.5	MONEL	STRAIGHT	HEAVY
11a	0.03	2.5	MONEL	STRAIGHT	TAPERED
11b	0.03	2.5	MONEL	STRAIGHT	TAPERED WITH SILVER JACKET
11c	0.03	2.5	MONEL	STRAIGHT	TAPERED WITH BRASS JACKET
12	0.0693	4.0	MONEL	STRAIGHT	TAPERED WITH BRASS JACKET
13	0.1613	3.0	MONEL	STRAIGHT	TAPERED
14	0.1303			STRAIGHT	TAPERED
15	0.462	67.4	MONEL	STRAIGHT	TAPERED
16	0.241	70.0	MONEL	STRAIGHT	TAPERED
17	0.668	153.0	MONEL	STRAIGHT	STRAIGHT
18	0.668	50.0	MONEL	STRAIGHT	STRAIGHT
19	0.668	7.5	MONEL	STRAIGHT	STRAIGHT
20	0.673	89.0	MONEL	DIVERGENT	STRAIGHT
21	0.545	81.0	MONEL	STRAIGHT	STRAIGHT
22	0.673	100.0	MONEL	STRAIGHT	HEAVY COPPER JACKET
23	0.545	81.0	COPPER	STRAIGHT	HEAVY
24	0.677	100.0	COPPER	STRAIGHT	WATER COOLED
25	0.241	70.0	COPPER	STRAIGHT	WATER COOLED
26	1.031	124.0	COPPER	STRAIGHT	WATER COOLED

TABLE XV

BURNING VELOCITY OF H_2-O_2 FLAMES AT 14.6 ATMOSPHERES

$\%H_2$	v_o	$\bar{U}_G$	R_e	$10^{-5}g^t$	U_F
30.0	38.9	37.7	8050	2.8	8.9
33.5	47.0	45.6	9400	3.9	9.8
35.3	55.4	53.8	10730	5.1	10.5
45.5	72.5	70.2	11900	7.4	14.8
49.6	78.5	76.0	12700	8.1	20.9
59.9	90.1	87.2	12460	9.2	32.3
64.1	82.6	80.0	10720	7.5	35.7
66.4	77.4	74.9	9650	6.5	33.5
69.9	75.5	73.1	8940	6.0	28.2
71.4	172.1	166.0	19750	24.8	28.1
72.6	70.1	67.9	7970	5.1	20.8
74.5	160.9	155.5	17570	21.2	22.7
79.0	197.4	189.8	19740	28.0	12.6
79.1	58.8	56.7	5860	3.4	17.5
81.0	35.5	35.6	3380	1.5	12.6
81.5	57.1	55.1	5365	3.1	13.4
82.7	47.1	45.6	4280	2.2	10.4